Recent results from XMASS

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Outline

- The XMASS experiment

- Recent dark matter results
  - Annual modulation search   [Phys. Lett. B759 (2016)272-276]
  - WIMPs search by fiducialization   **New results !!**

- Supernova neutrino detection via coherent scattering
  [Astropart. Phys. 89 (2017) 51-59]

- Summary

The XMASS project

● XMASS: a multi purpose experiment with liquid xenon

● Located 1,000 m underground (2,700 m.w.e.)
  at the Kamioka Observatory in Japan

● Aiming for
  ● Direct detection of dark matter
  ● Observation of low energy solar neutrinos ($pp/^7$Be)
  ● Search for neutrino-less double beta decay

● Features
  ➢ Low energy threshold (~0.5keVee)
  ➢ Sensitive to e/γ events as well as nuclear recoil
  ➢ Large target mass and its scalability

KamLAND

Super-Kamiokande

CANDLES

XMASS

E-GADS

NEWAGE   CLIO

3
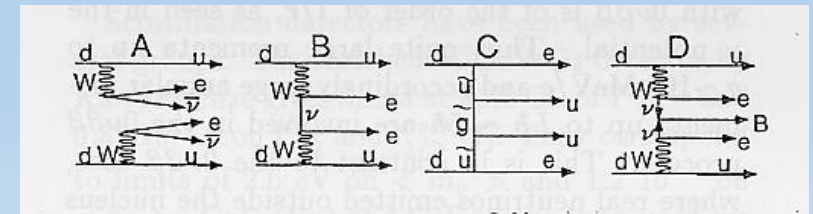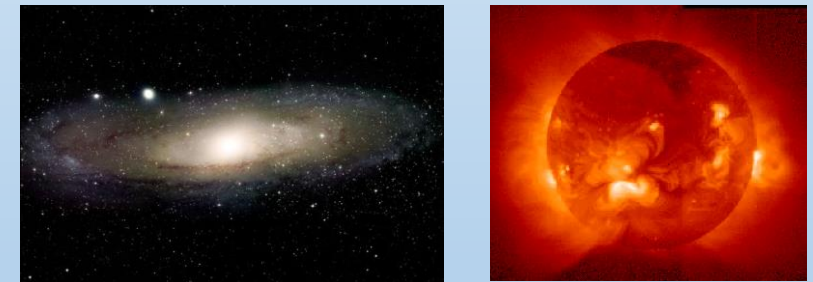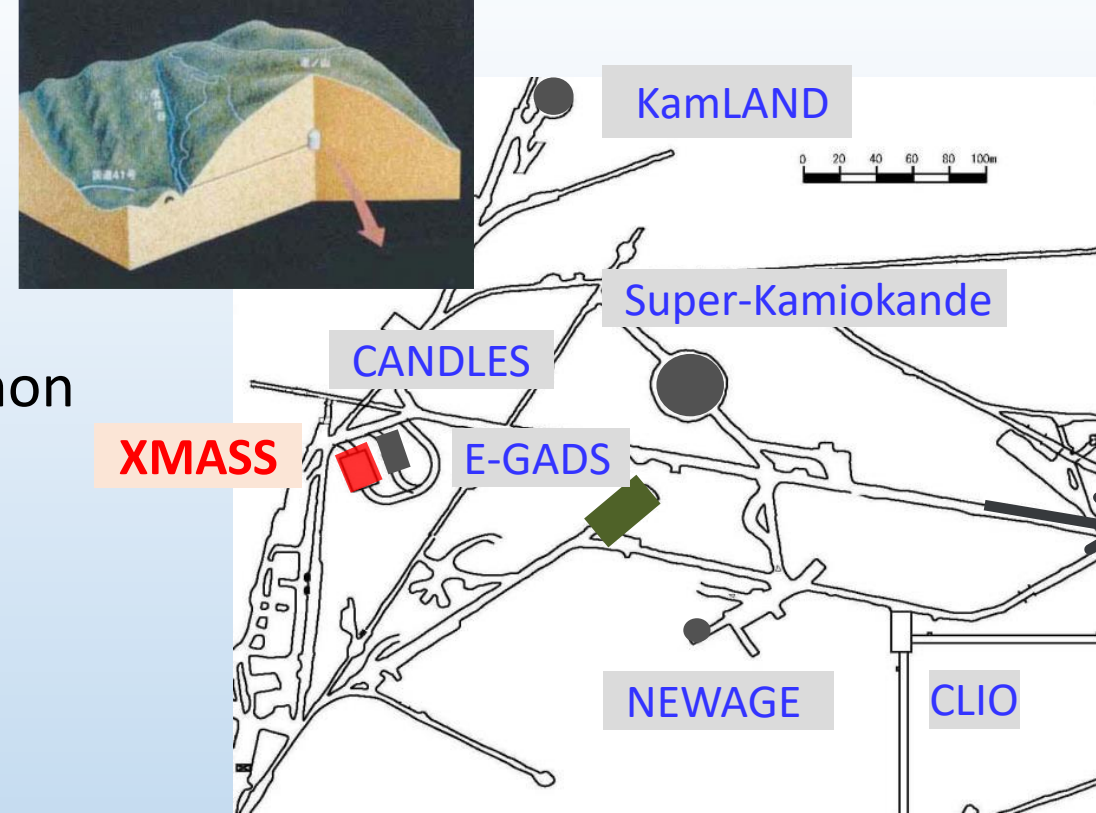
# Single-phase liquid Xenon detector: XMASS-I

11m

10m

80cm
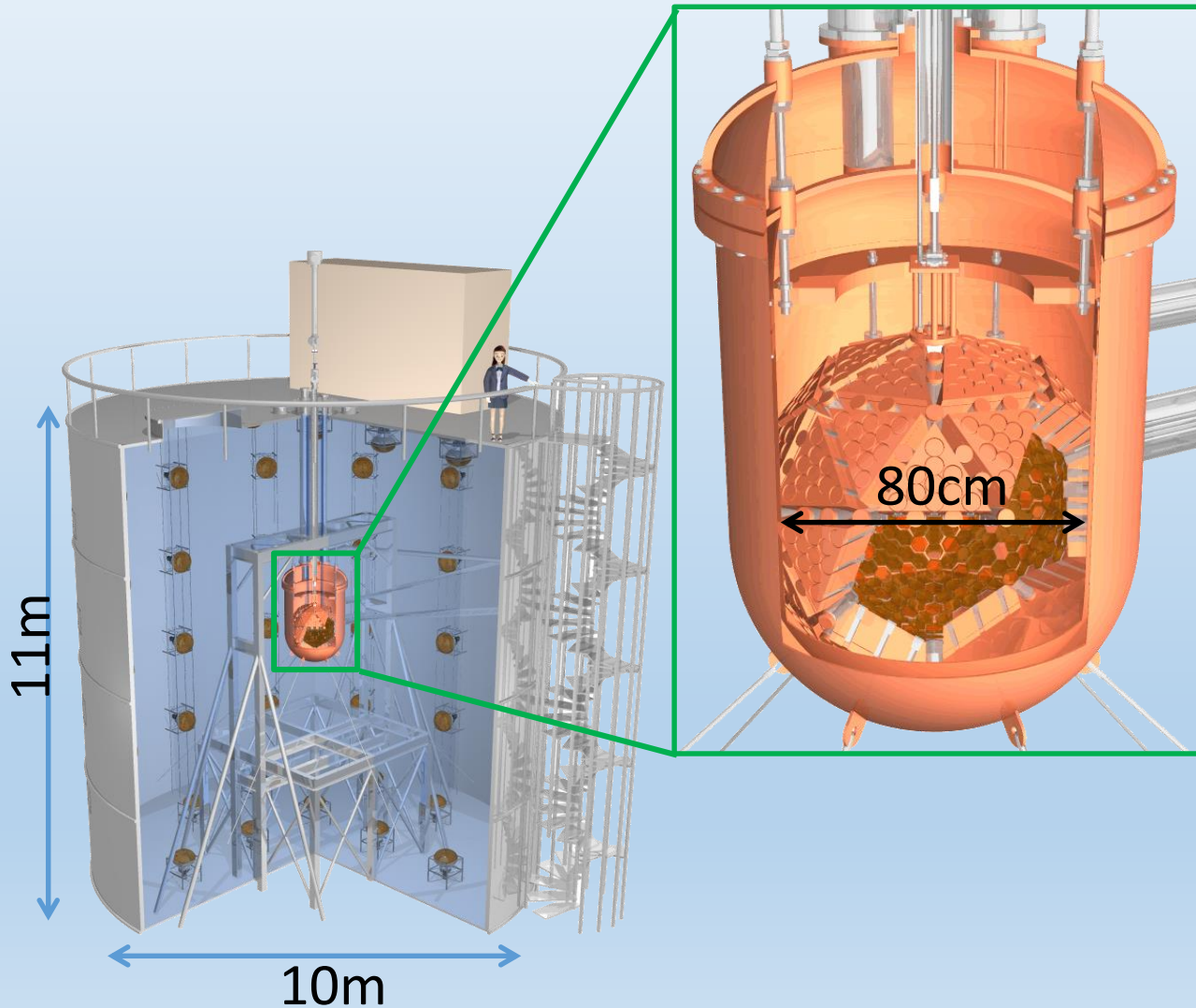
- Liquid xenon detector
  - 832 kg of liquid xenon (-100 °C)
  - 642 2-inch PMTs (Photocathode coverage >62%)
  - Each PMT signal is recorded by 10-bit 1GS/s waveform digitizers

- Water Cherenkov detector
  - 10m diameter, 11m high
  - 72 20-inch PMTs
  - Active shield for cosmic-ray muons
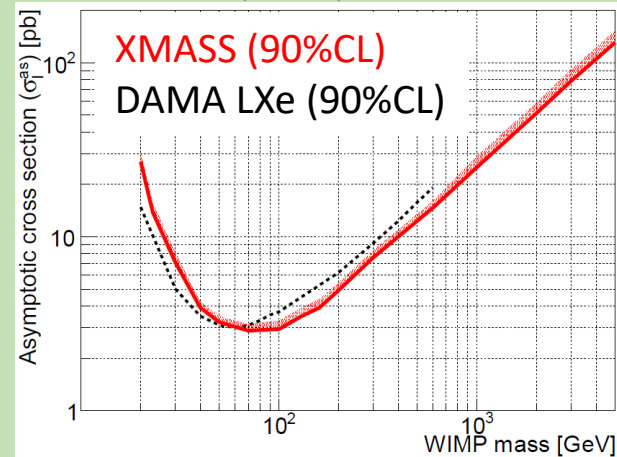 - Passive shield for n/γ

4

Diversity of physics target with XMASS
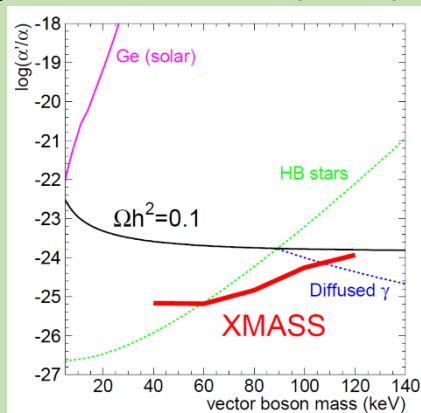
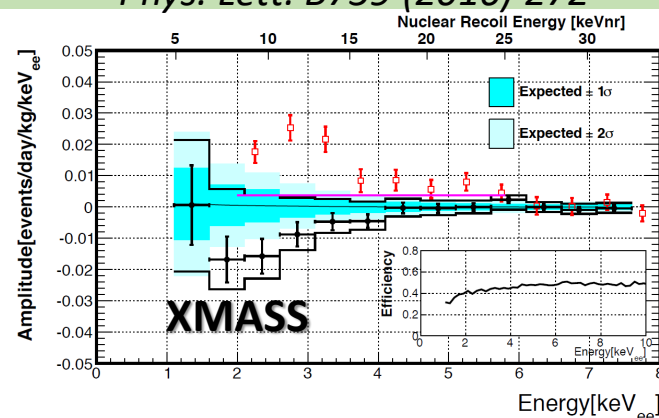## ■ Dark matter searches

Low mass WIMP search
Phys. Lett. B719 (2013) 78
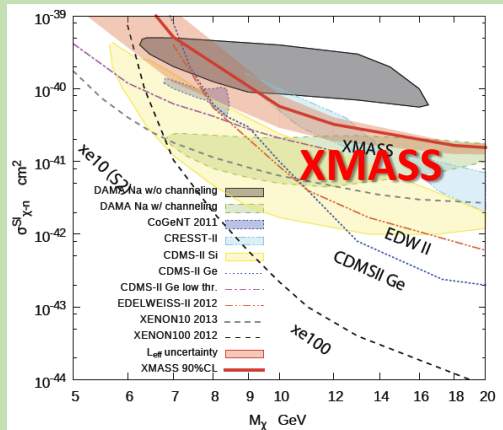
WIMP-^{129}Xe inelastic scattering
PTEP (2014) 063C01

XMASS (90%CL)
DAMA LXe (90%CL)

Bosonic super-WIMPs search
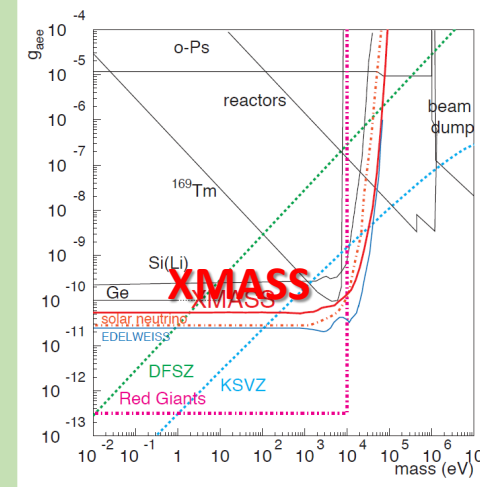*Phys. Rev. Lett. 113 (2014) 121301*

Annual modulation search
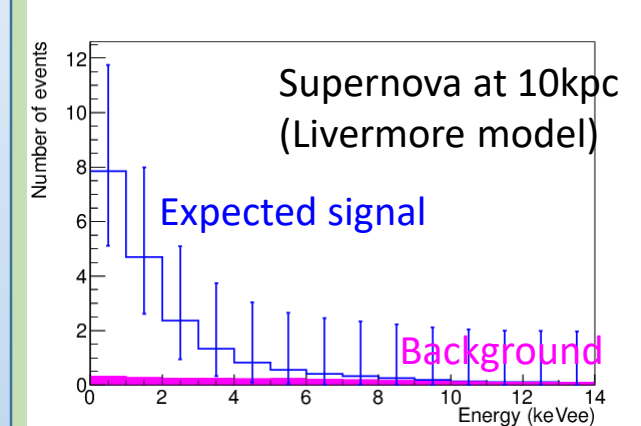*Phys. Lett. B759 (2016) 272*

■ Solar axion search

Phys. Lett. B724 (2013) 46

■ Possibility of supernova neutrino detection

*Astropart. Phys. 89 (2017) 51*


Supernova at 10kpc
(Livermore model)
Expected signal
Background

■ Search for 2ν double electron capture on ^{124}Xe, ^{126}Xe

Observed data
Expected signal
^{214}Pb background
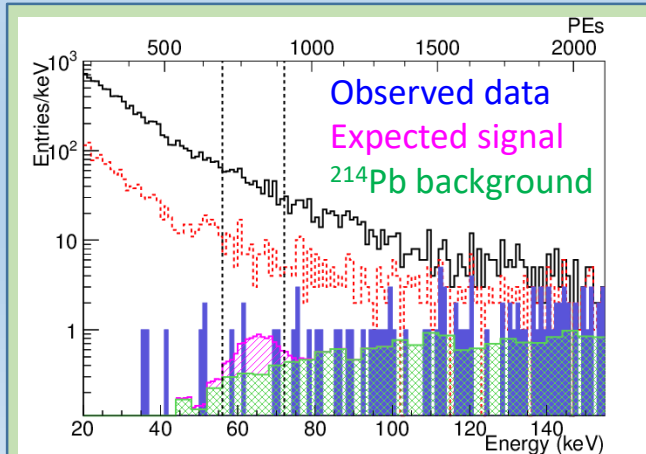
Phys. Lett. B759 (2016) 64

Search for annual modulation

- Expect annual modulation of event rate of dark matter signal due to Earth's rotation around the Sun.
- DAMA/LIBRA claims modulation at 9.3σ
  - Total exposure of 1.33 ton year (14 cycles)
  - Modulation amplitude of (0.0112+/-0.0012) cpd/kg/keV for 2-6 keV
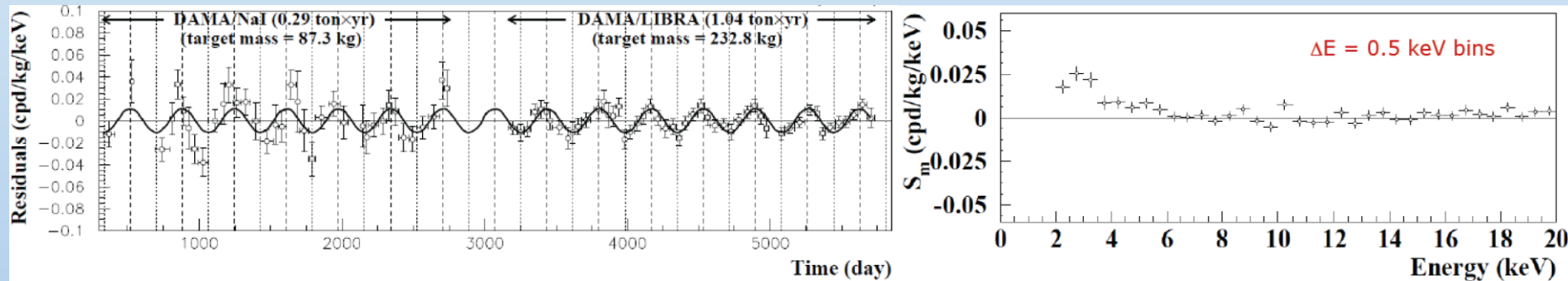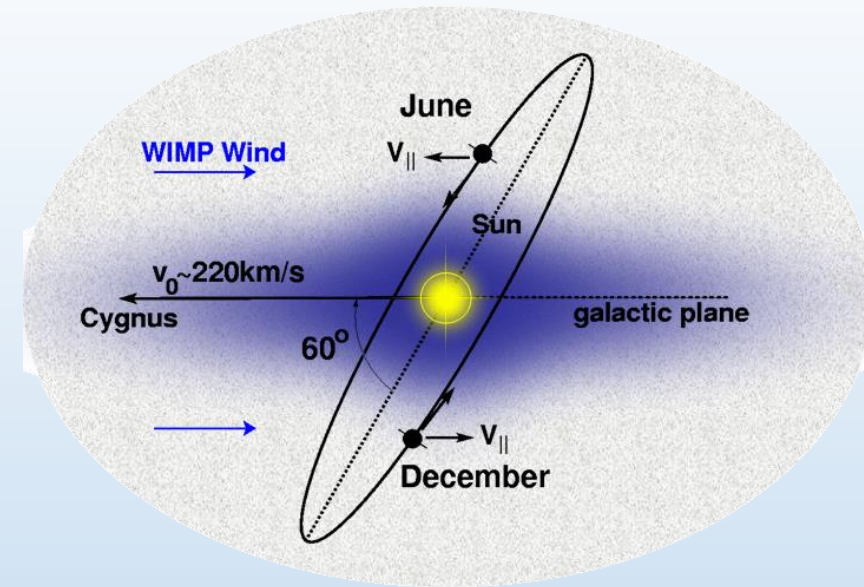
- Annual modulation search in XMASS
  - 359.2 live days x 832 kg (=0.82 ton year)
  - Analysis threshold 1.1 keVee (=4.8 keVnr)
  - Look for event rate modulation not only for nuclear recoil but also for e/γ events
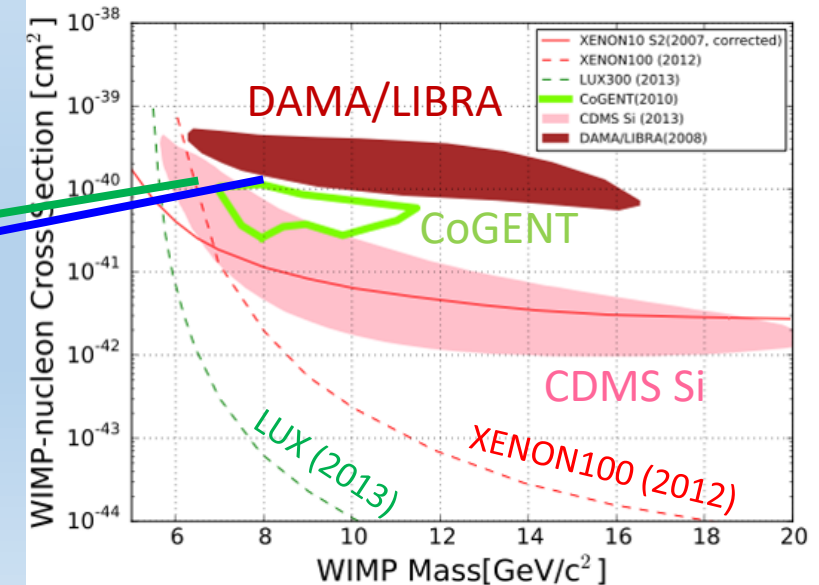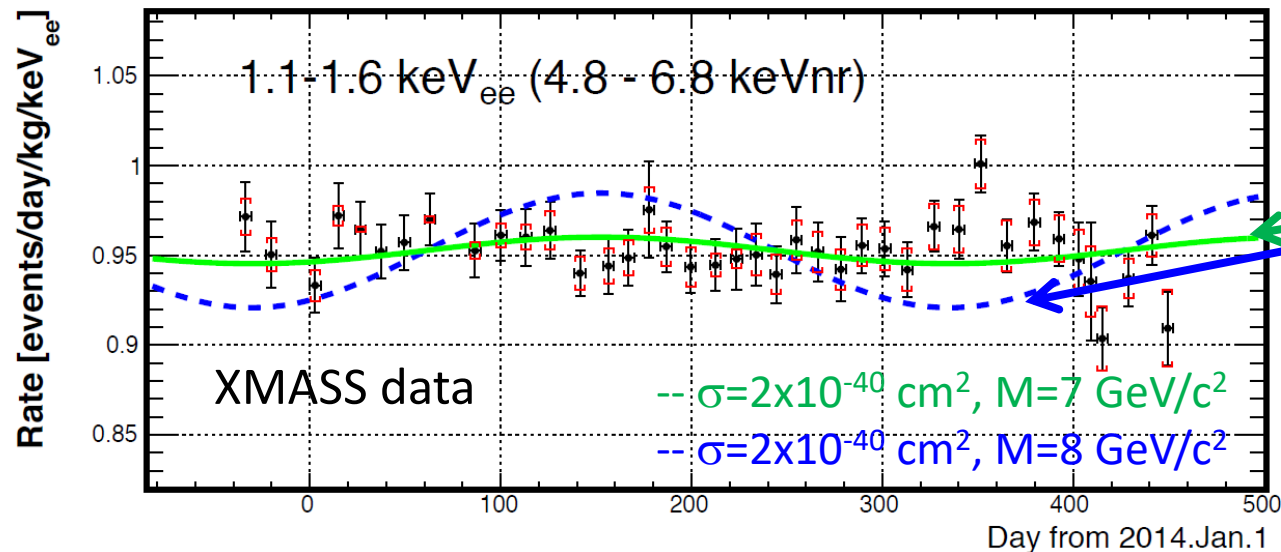
Modulation analysis

- Two different fitting methods

  Pull term
  (Method-1)

  $$\chi^2 = \sum_i^{E_{bins}} \sum_j^{t_{bins}} \left(\frac{(R_{i,j}^{\text{data}} - R_{i,j}^{\text{ex}} - \alpha K_{i,j})^2}{\sigma(\text{stat})_{i,j}^2 + \sigma(\text{sys})_{i,j}^2} \right) + \alpha^2$$

  Covariance matrix
  (Method-2)

  $$\chi^2 = \sum_{k,l}^{N_{bins}} (R_k^{\text{data}} - R_k^{\text{ex}})(V_{\text{stat}} + V_{\text{sys}})_{kl}^{-1}(R_l^{\text{data}} - R_l^{\text{ex}})$$

- Our data demonstrate high sensitivity to modulation
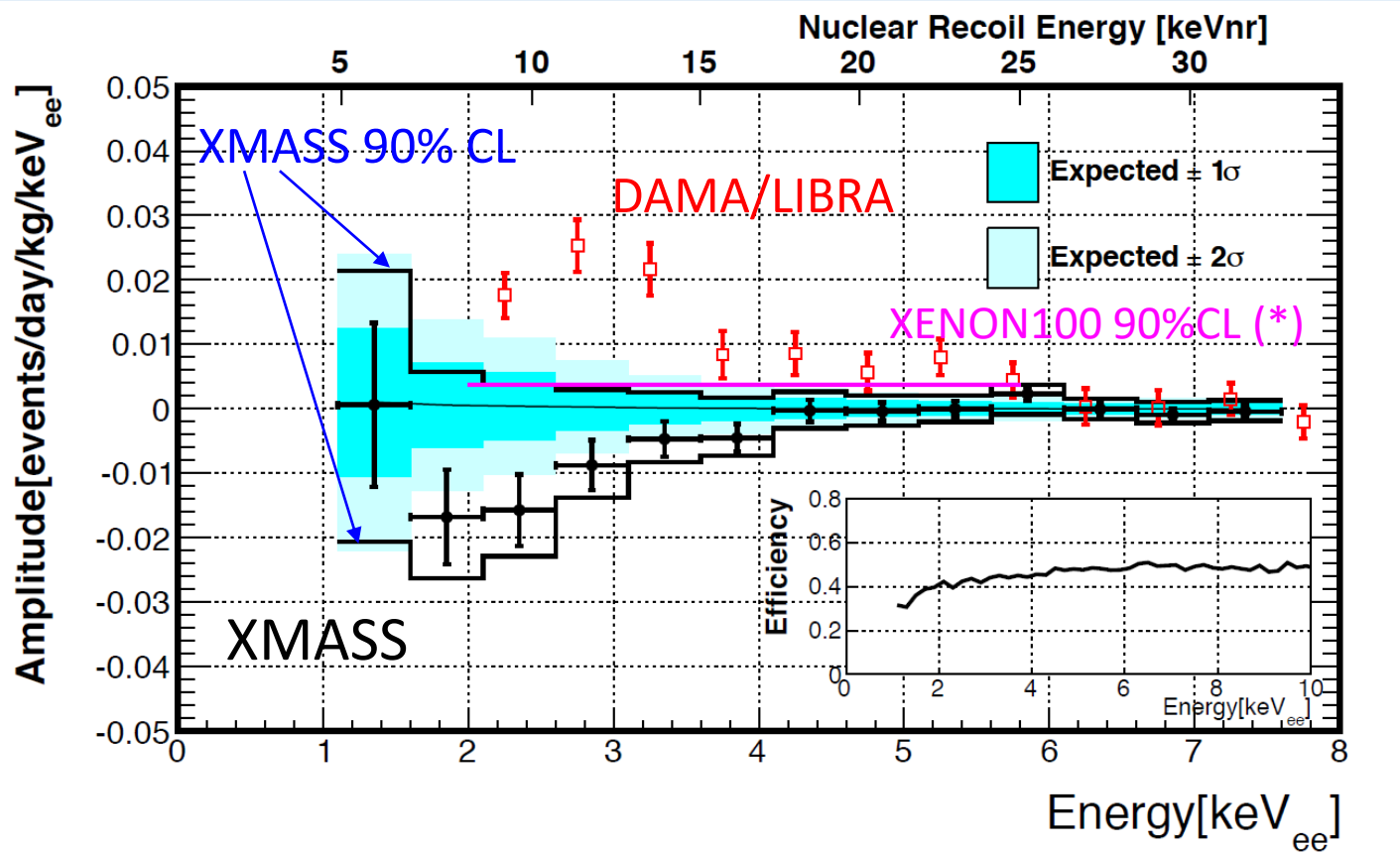
Modulation analysis: WIMP results
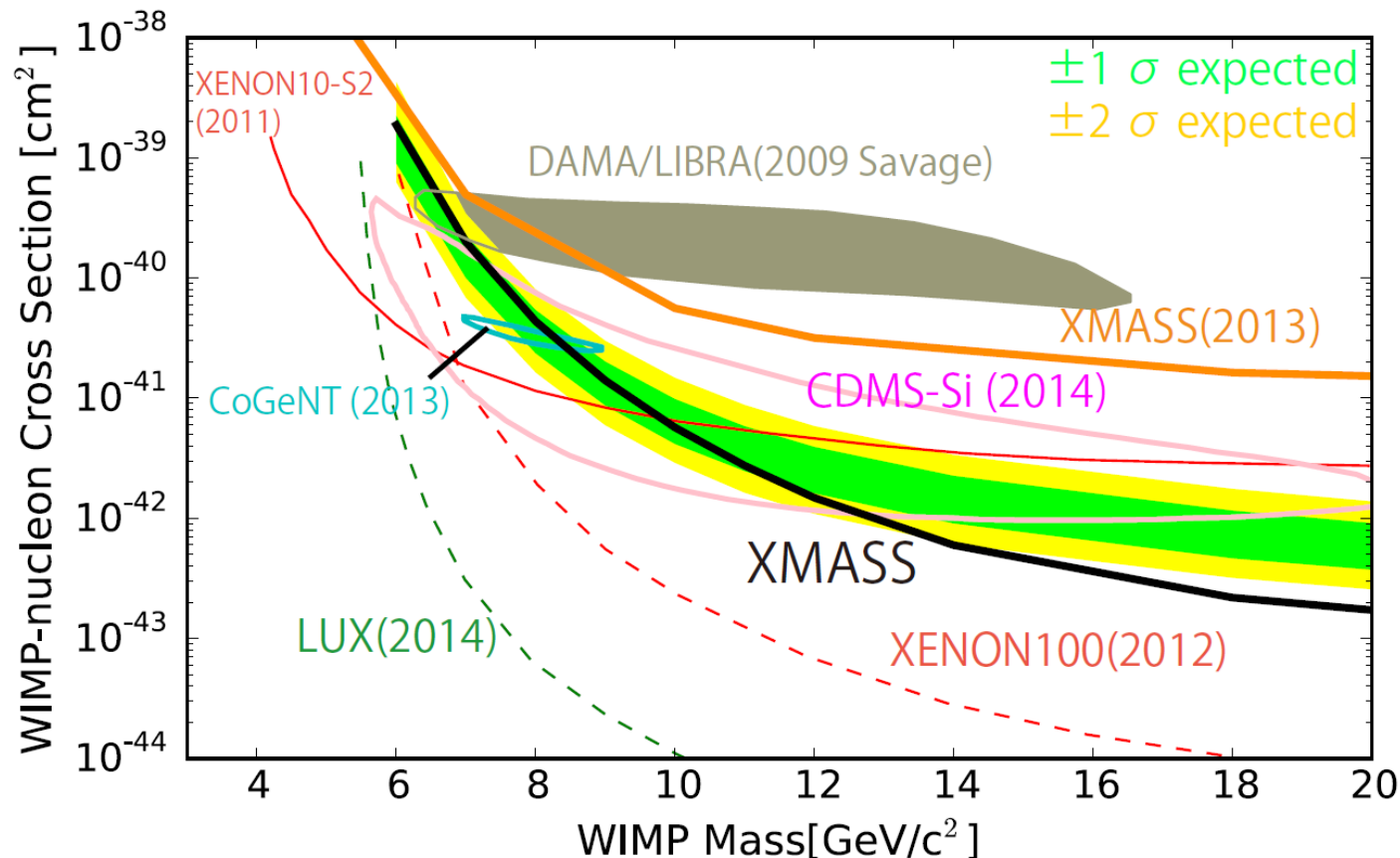
- Expected event rate

$$R_{i,j}^{\text{ex}} = \int_{t_j - \frac{1}{2}\Delta t_j}^{t_j + \frac{1}{2}\Delta t_j} \left(C_i + \sigma_{\chi n} \cdot A_i(m_\chi) \cos 2\pi \frac{(t - t_0)}{T} \right) dt$$

  ➢ T= 1year, t_0=152.5 day (fixed)
  ➢ Ai(m_χ): modulation amplitude
  ➢ Ci: unmodulated event rate

- WIMP mass range 6 to 20 GeV/c^2
- Both fitting methods give similar results
- Exclude almost all the DAMA/LIBRA allowed region by modulation search

# Modulation analysis: model independent results

(*) We estimated the XENON100 90% CL limit based on PRL 115 (2015) 091302 and Science 349 (2015) 852.

- Without assuming any specific model except for T=1 year, t_0=152.5 day
- Includes both NR and e/γ signals

- Shows slightly negative amplitudes in the 1.6-4.1 keVee range.

- P-values
  - ➢ 0.014 (2.5σ) for method-1
  - ➢ 0.068 (1.8σ) for method-2

- Gives 90% CL limits for positive and negative amplitude separately
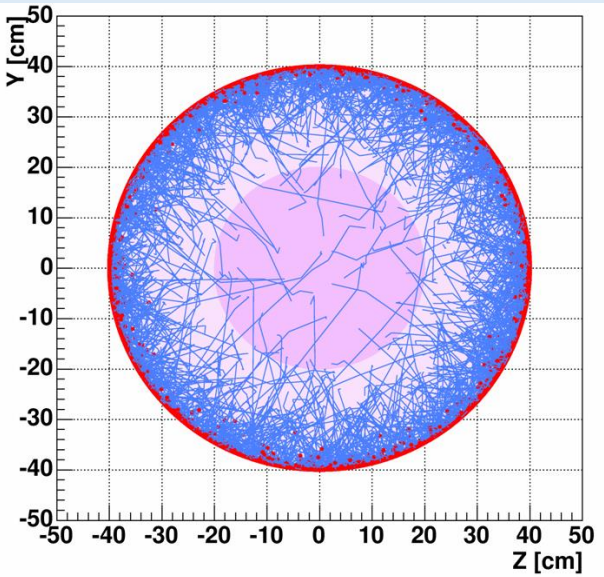
Phys. Lett. B759 (2016) 272

9

Modulation search with 2.7 years data
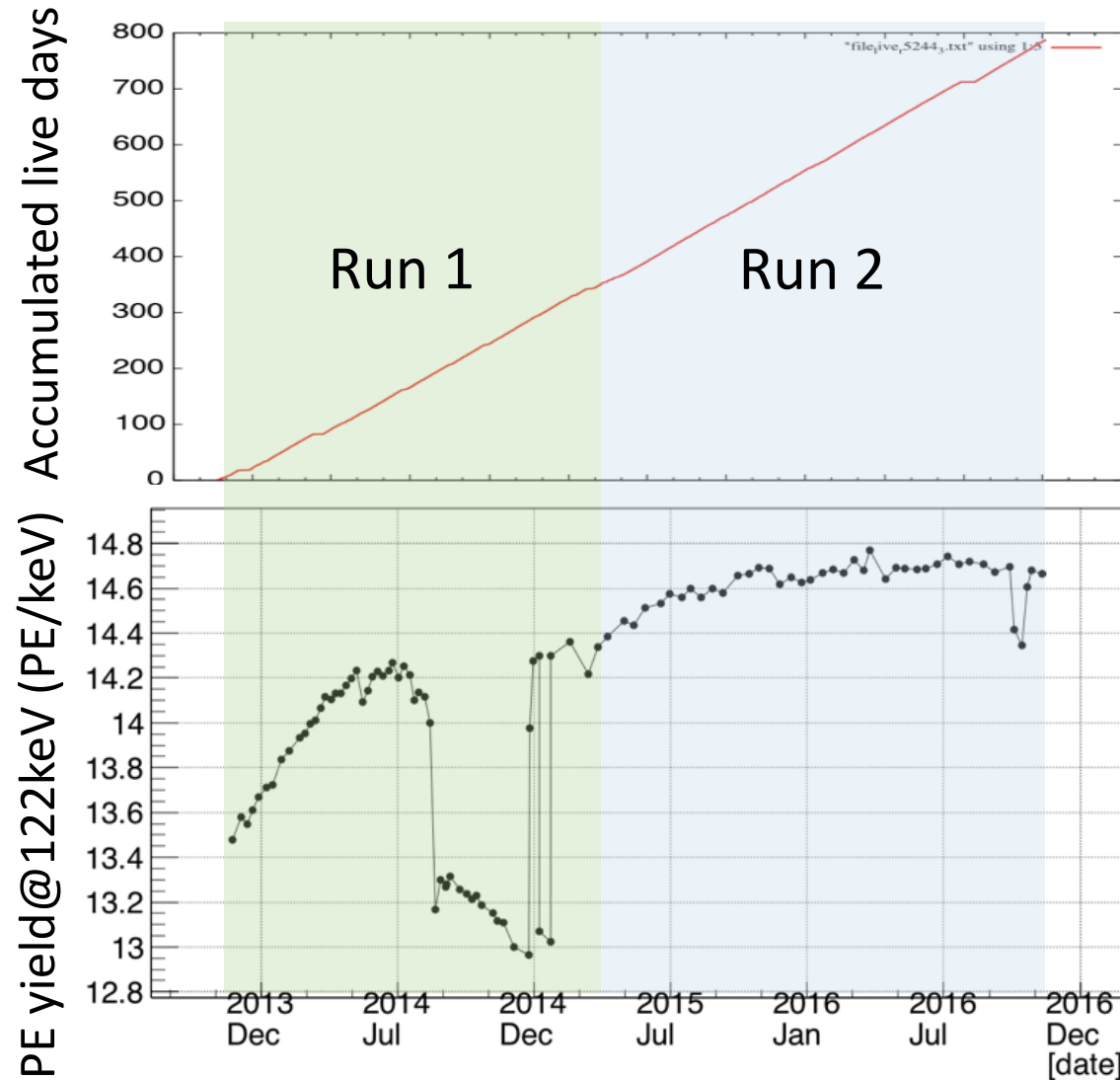
- Accumulated 800 live days of data until Aug. 2016.

- Achieved stable detector operation especially during run 2

- Will perform frequency and phase analyses

- Results will come soon.

WIMPs search by fiducialization

Reconstructed vertex

Traces of γ-rays from PMTs

DATA   MC

- Self-shielding of external γ-rays owing to high atomic number (Z=54) and high density (2.9g/cm3)

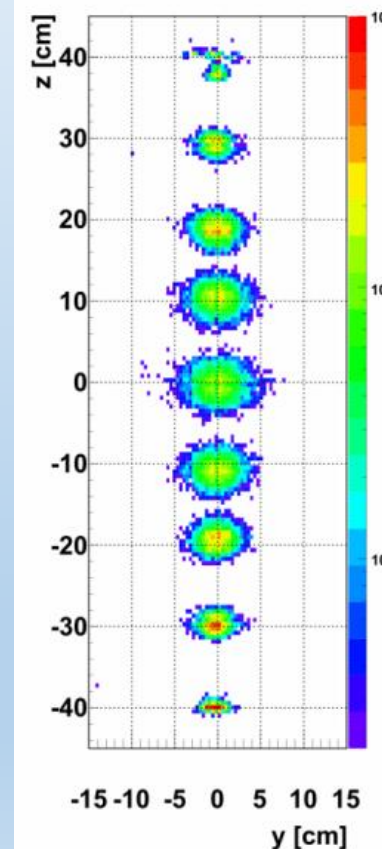- Event vertex position and energy are reconstructed using number of PE in each PMT

$$L(\mathbf{x}) = \prod_{i=1}^{642} p_i(n_i)$$

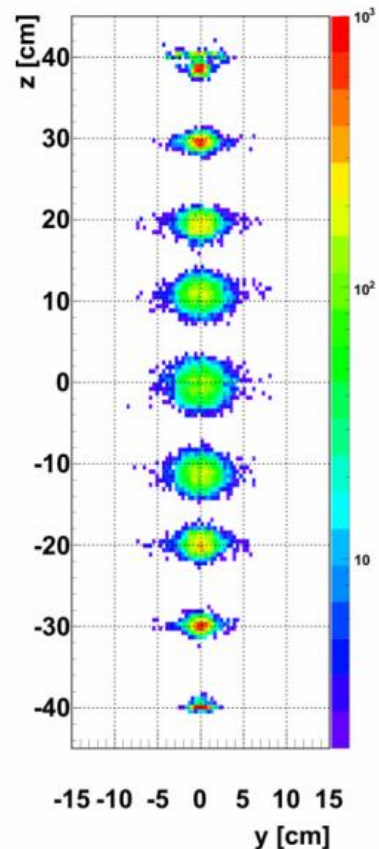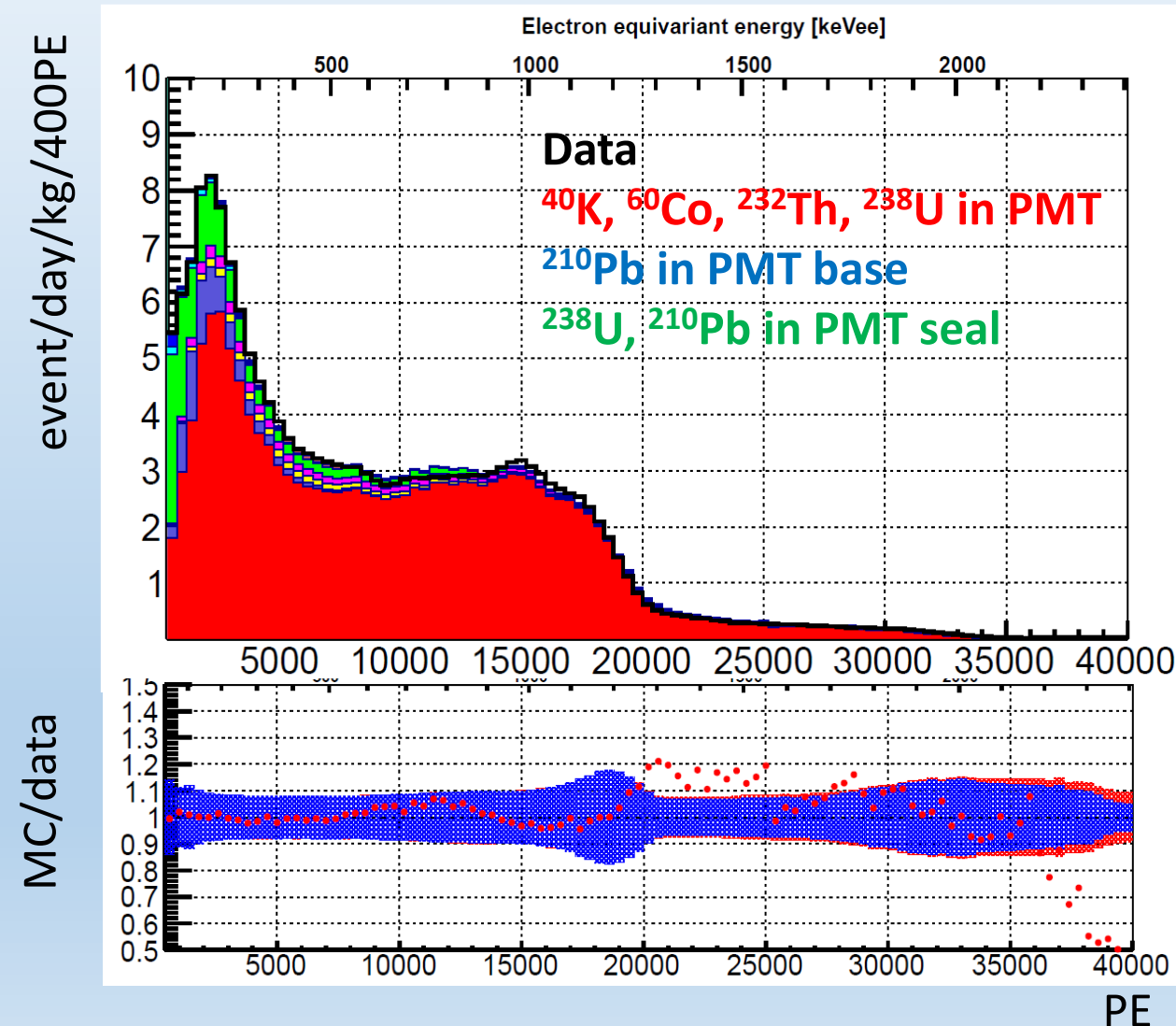P_i (n) : probability that the i-th PMT detects n PE

Fiducial volume
R<20cm

Background understanding w/o fiducialization

- All the detector material was screened by the Ge detector before installation.
- The energy spectrum above 30 keV was fitted under the constraints by the screening results.
- Alpha-ray events are selected using scintillation decay time. They are used to constrain PMT/copper surface/bulk ^{210}Pb.
- Contamination of ^{210}Pb (~20 mBq/kg) in the bulk of oxygen-free copper was identified by the low background alpha-particle counter (XIA Ultra-Lo-1800)
  ➔ paper in preparation

Energy spectrum after fiducialization

- 706 live days taken in Nov. 2013 – Mar. 2016
- Fiducial mass 97kg (R<20cm)

WIMP search region (2-15keVee)

Energy (keVee)
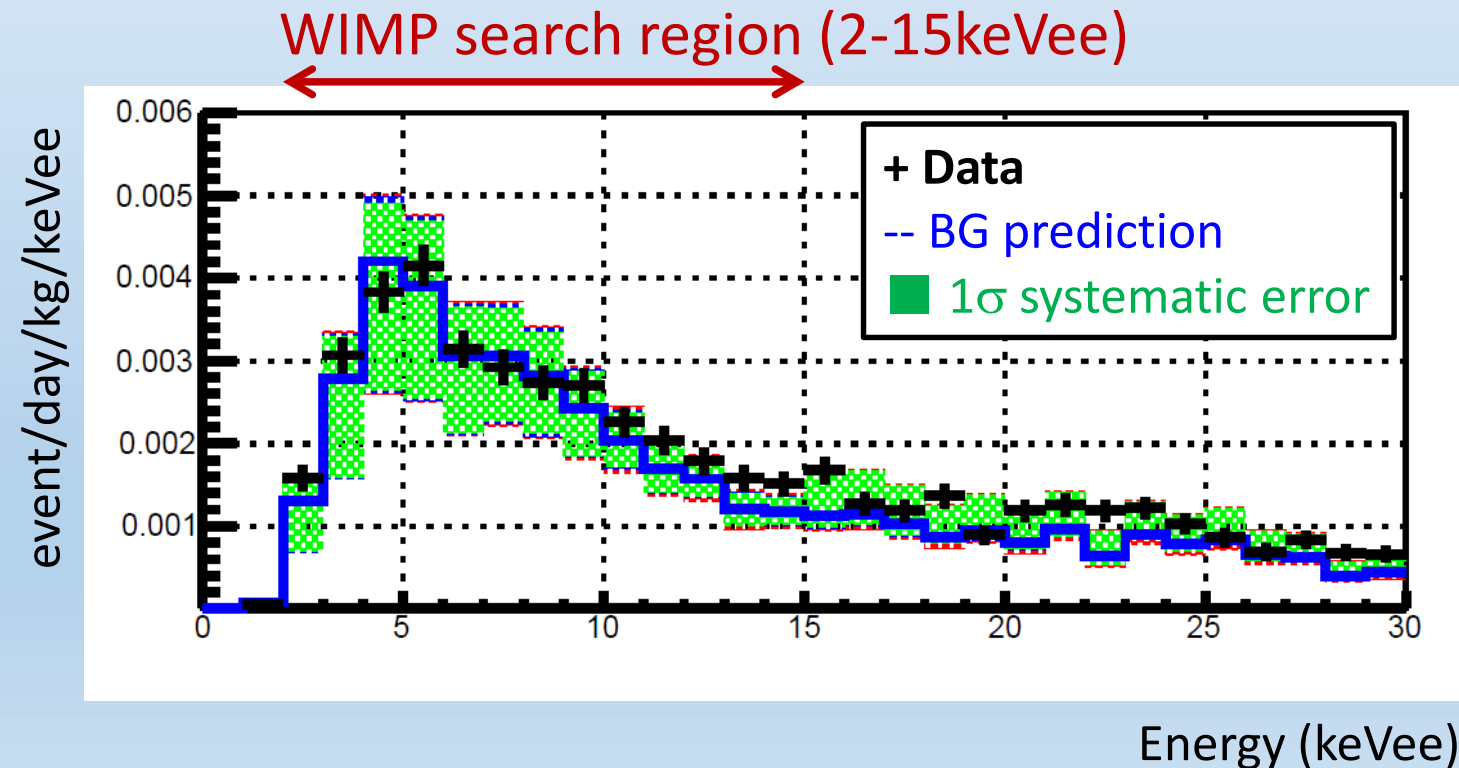
- Main BG in the WIMP search region
  - ^{210}Pb in the copper bulk
  - γ-rays from PMTs

- Internal RIs dominate above 15keVee
- Neutrons, alpha-rays are negligible

- Dominant systematic uncertainty is condition of detector inner surface (gap size, surface roughness)

WIMP search result

- The energy spectrum at 2-15 keVee is fitted with signal + BG
- Systematic uncertainties are taken into account as nuisance parameters
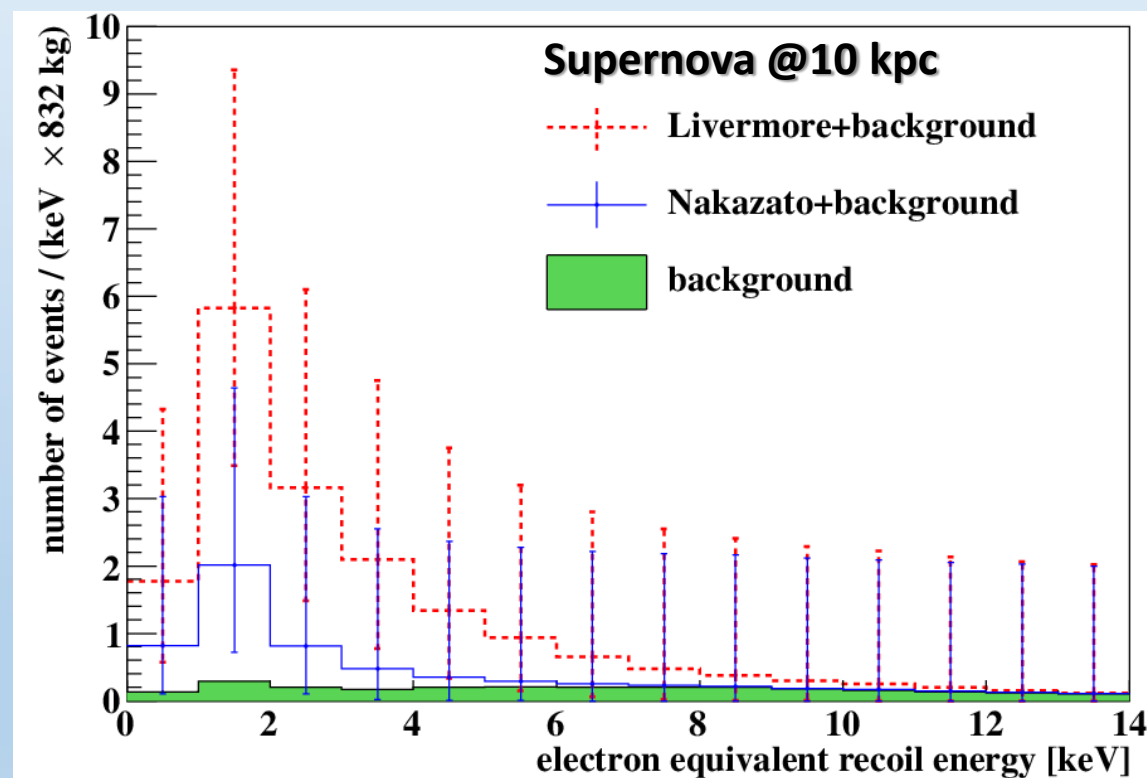- 90% CL upper limit on spin-independent WIMP-nucleon cross section is derived
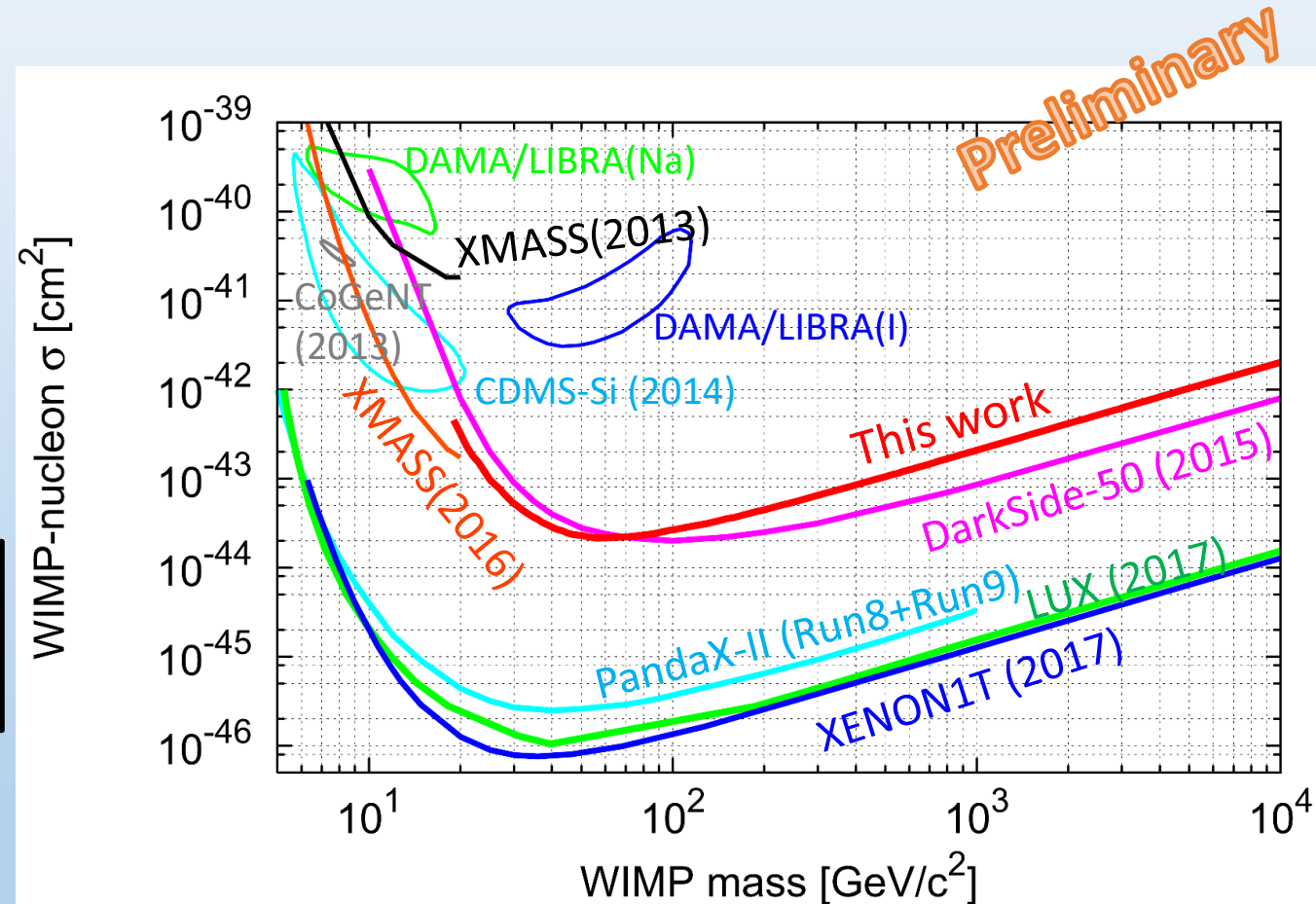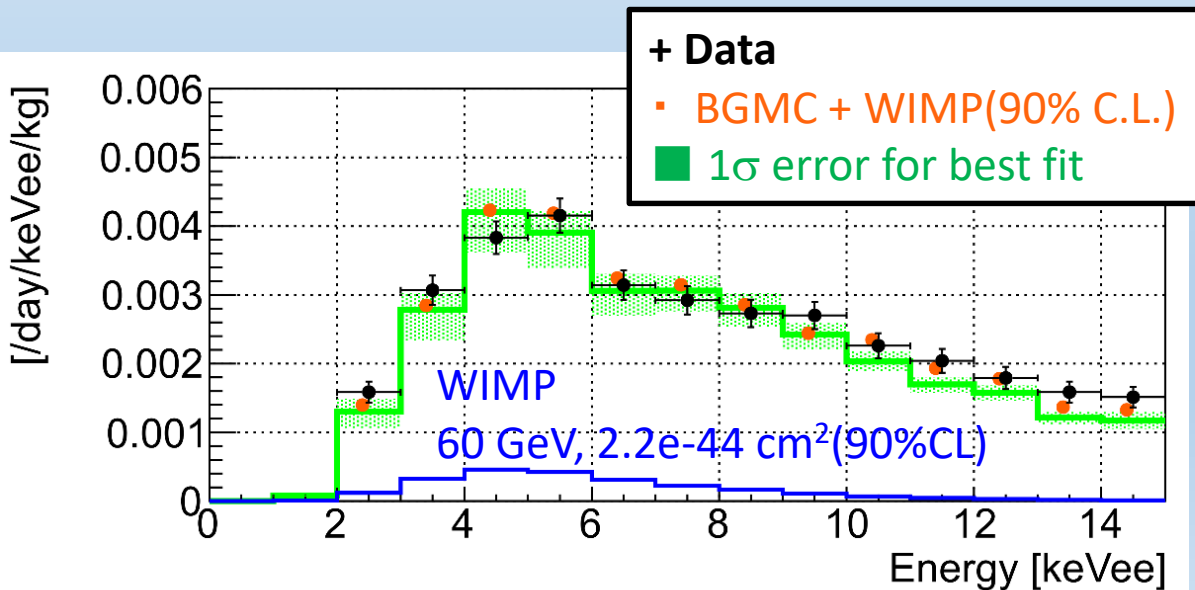
$\sigma_{SI} < 2.2 \times 10^{-44}$ cm^2 (90%CL, for 60 GeV/c^2 WIMP)

Supernova neutrino detection via coherent scattering

- Coherent elastic neutrino-nucleus scattering (CEvNS)

$$\nu_x + A \rightarrow \nu_x + A$$

  - Sensitive to all neutrino flavors
  - Nuclear recoil with less than a few ten's keV

- Large dark matter detectors are sensitive to galactic supernova neutrinos via CEvNS.

- In the case of supernova at 10 kpc, 3.5-21 events are expected in 18 sec depending on the supernova models.

- For Betelgeuse (196 pc), ~10^4 events are expected.

Supernova @10 kpc
- Livermore+background
- Nakazato+background
- background

number of events / (keV ×832 kg) vs electron equivalent recoil energy [keV]

15

Summary

- XMASS is a multi-purpose experiment using liquid xenon.
- Annual modulation search
  - With 1-year of data, no significant modulation was observed.
  - Results from 2.7 years of data will come soon.
- WIMP search by fiducialization
  - 706 live days x 97 kg fiducial mass
  - Limit on SI WIMP-nucleon cross section $\sigma < 2.2 \times 10^{-44}$ cm^2 for 60 GeV/c^2
- XMASS is waiting for neutrinos from galactic supernovae
- More physics results will be presented at coming summer conferences. Stay tuned!!

Backup slides

Search for light WIMPs

- Use full volume of LXe
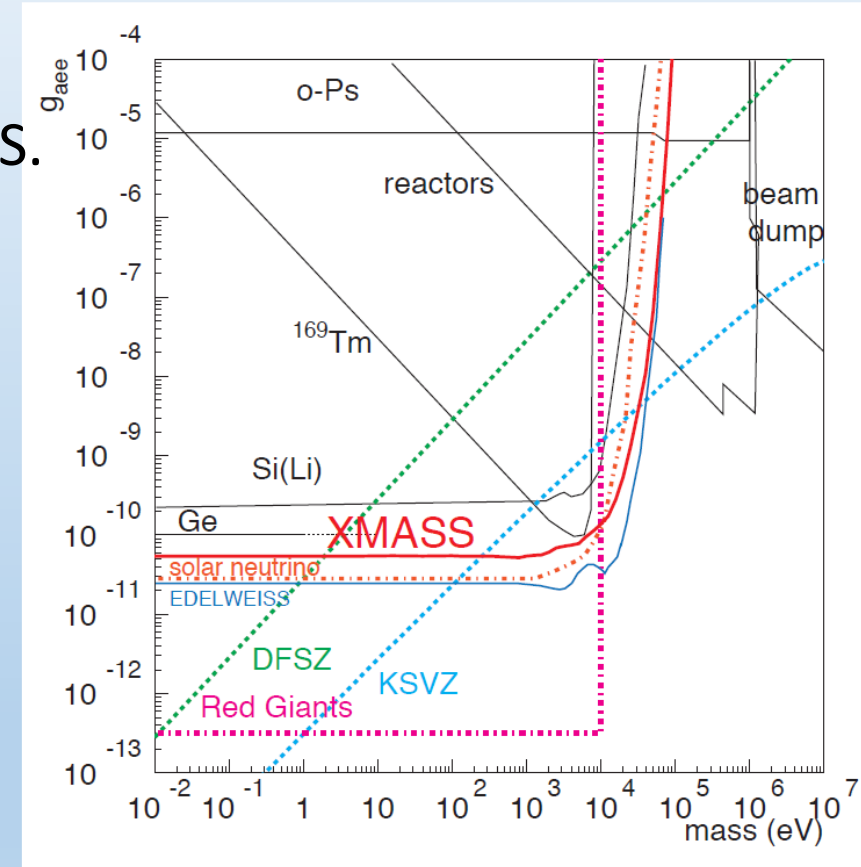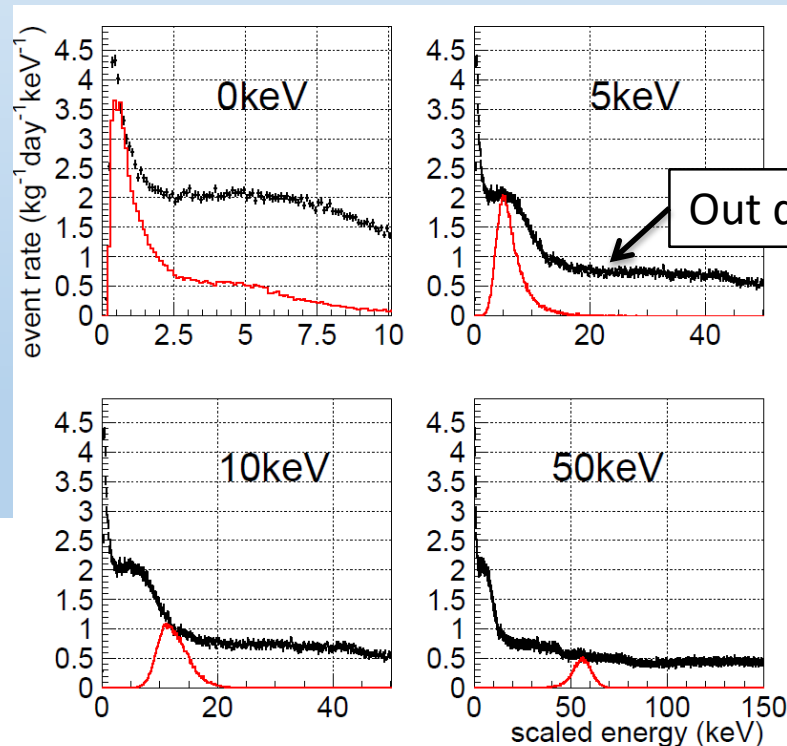- 6.7 days x 835 kg
- 0.3 keVee threshold
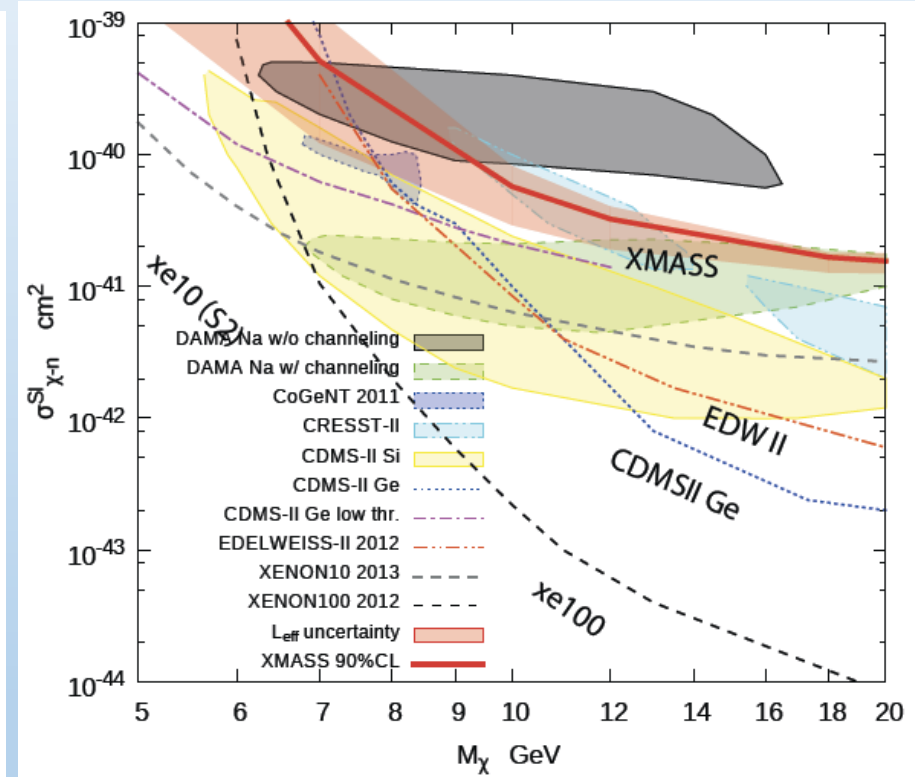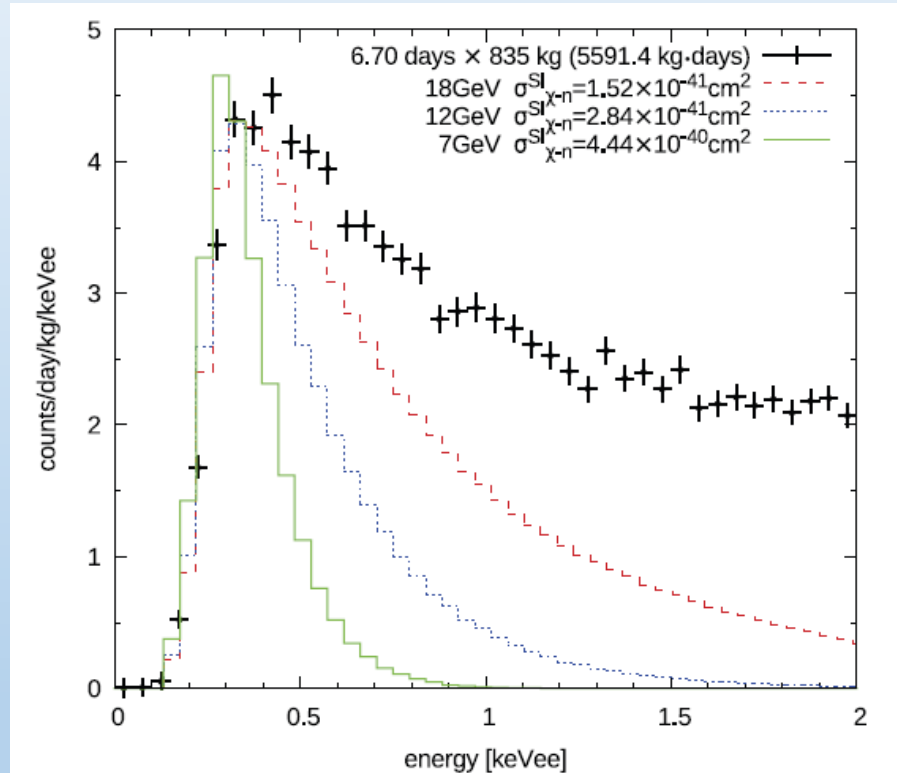
Search for solar axions

- Axions can be produced in the sun by bremsstrahlung and Compton effect, and detected by axio-electric effect in XMASS.
- Used the same data set as the light WIMPs search.
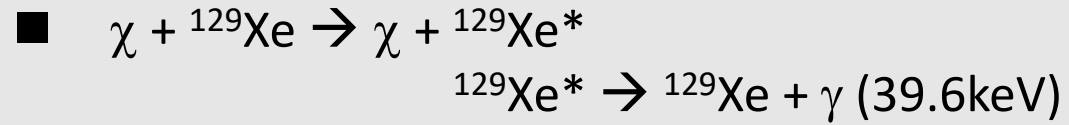
Bremsstrahlung and Compton effect

g_{aee}

Axio-electric effect

g_{aee}

0keV

5keV
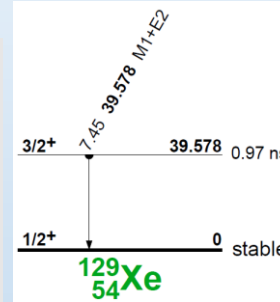
Out data

10keV

50keV

Published in Phys. Lett. B 724 46 (2013)

Search for ^{129}Xe inelastic scattering by WIMPs

- $\chi + {}^{129}\text{Xe} \rightarrow \chi + {}^{129}\text{Xe}^*$
  $^{129}\text{Xe}^* \rightarrow {}^{129}\text{Xe} + \gamma$ (39.6keV)

- Natural abundance of ^{129}Xe: 26.4%

Signal MC for 50GeV WIMP

(1)= pre-selection
(2)= (1) & radius cut
(3)= (2) & timing cut
(4)= (3) & band cut
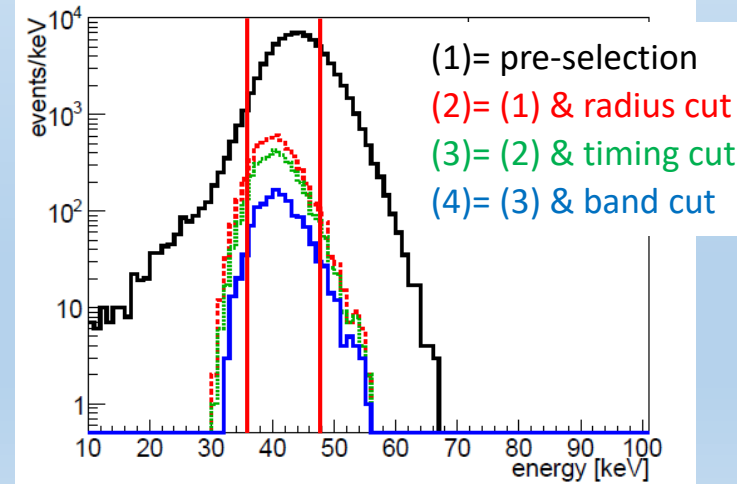
Observed data (165.9 days)

Red: XMASS (90% C.L. stat. only)
Pink band: XMASS (w/ sys. error)
Black: DAMA LXe 2000 (90% C.L.)
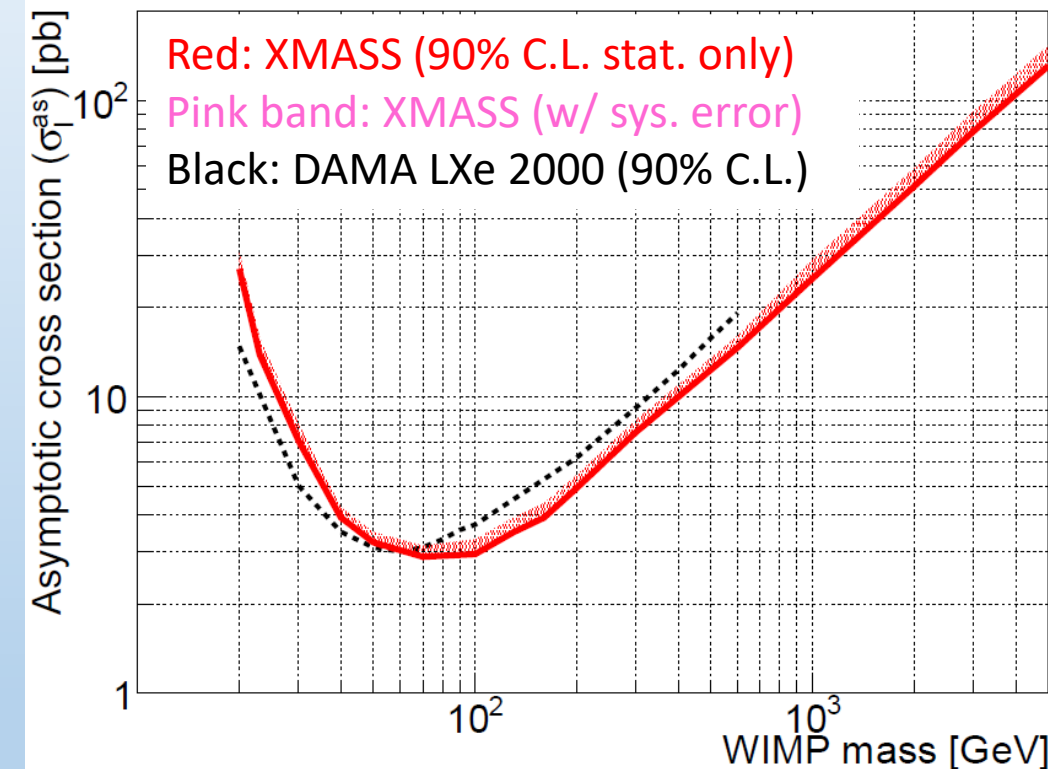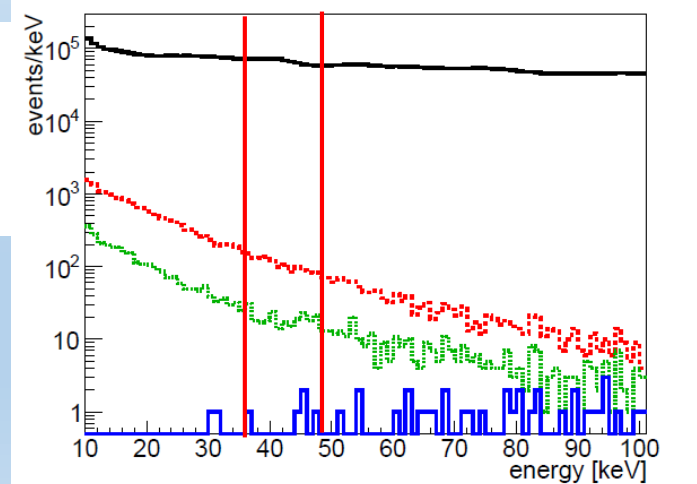
Published in PTEP 063C01 (2014)

Search for bosonic super-WIMPs
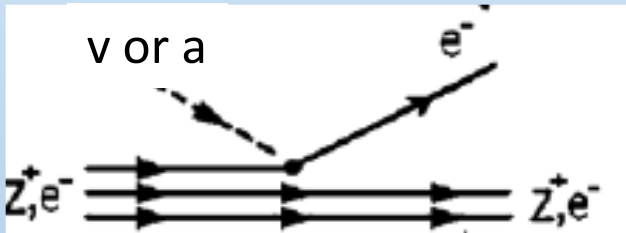
● Bosonic super-WIMPs

> Lighter and more weekly interacting than WIMPs
> Candidate for lukewarm dark matter
> Can be pseudoscaler or vector boson.
> Can be detected by absorption of the particle, which is similar to the photoelectric effect.

v or a

● Search for bosonic super-WIMPs in XMASS

> 165.9 days data taken in Dec. 2010 – May 2012
> 41 kg fiducial mass
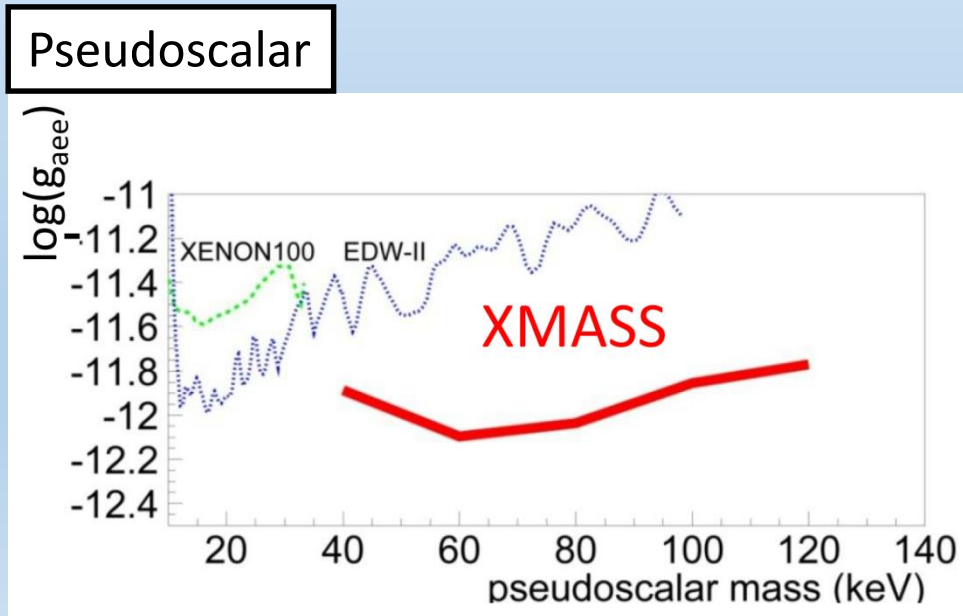> Remaining event rate ~10^{-4} dru (^{214}Pb from ^{222}Rn)
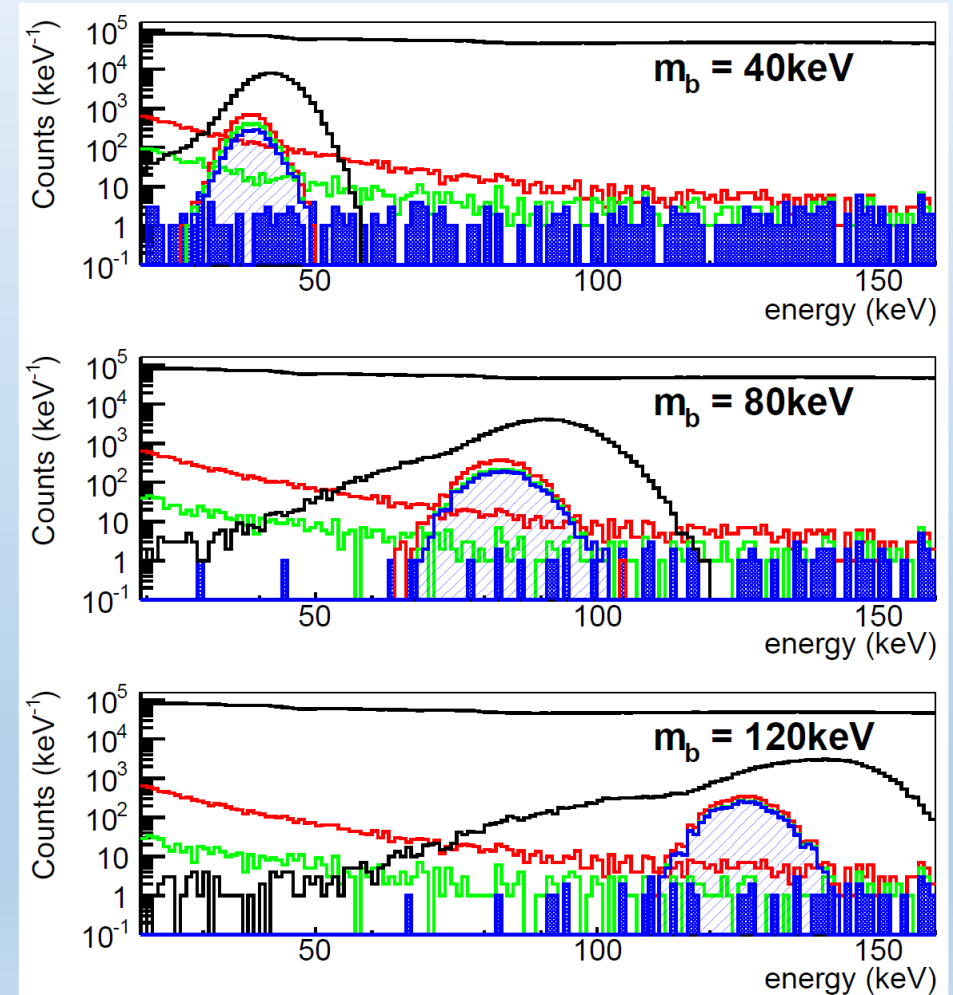
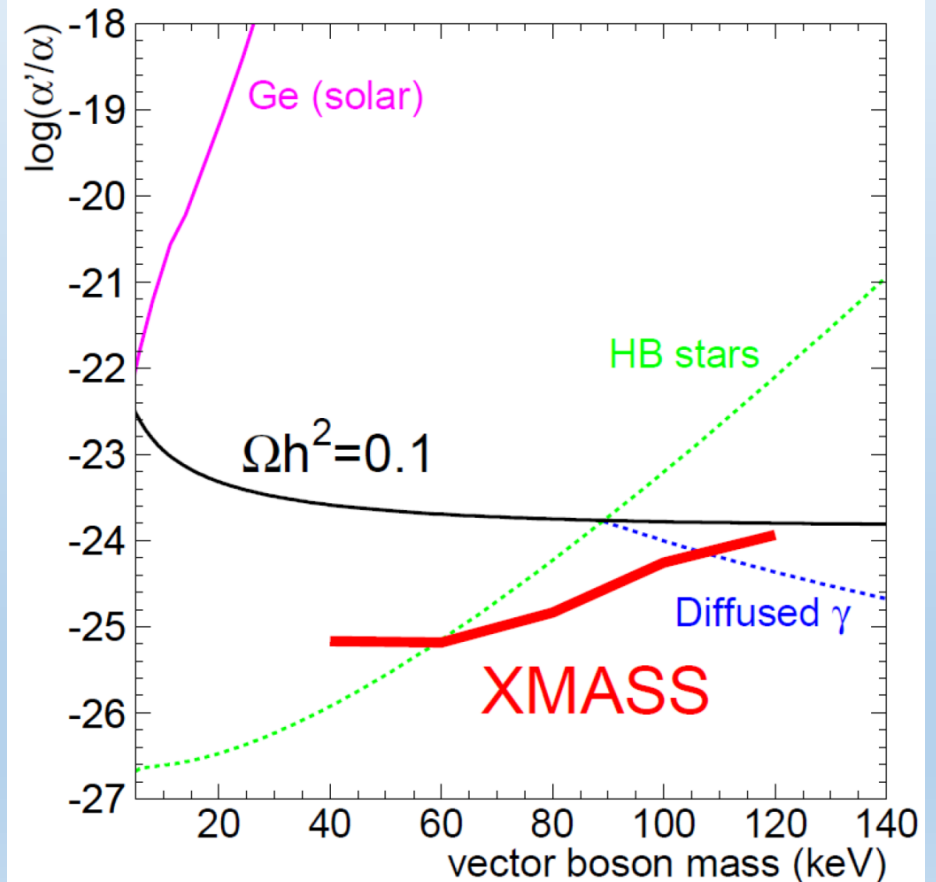# Constraint on coupling constants

- **Vector boson case**
  - ➤ The first direct search in the 40–120 keV range.
  - ➤ We exclude the possibility that such particles constitute all of dark matter.
- **Pseudoscaler case**
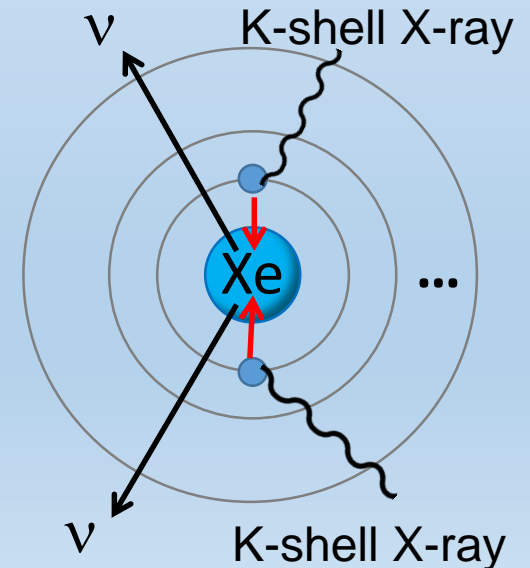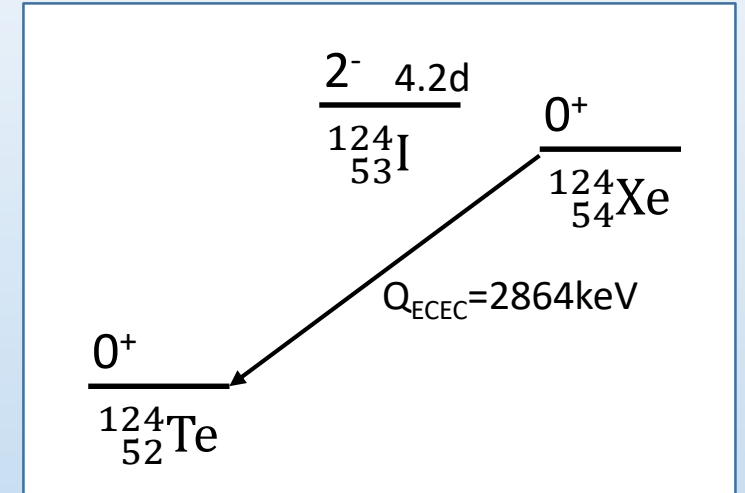 - ➤ The most stringent direct constraint on g_{aee}.

Pseudoscalar

Vector boson

Phys. Rev. Lett. 113 (2014) 121301

2ν double electron capture on ^{124}Xe

- Natural xenon contains ^{124}Xe (N.A.=0.095%) which can undergo 2νECEC.

  ^{124}Xe (g.s., 0^+) + $2e^-$ → ^{124}Te (g.s., 0^+) + $2\nu_e$ + 2864keV

- In the case of 2 K-shell electrons are captured,
  - Only X-rays and Auger electrons are observable
  - Total energy deposit is 2 x E_B =63.6 keV

- Expected half-life is 10^{20}-10^{24} years.

- ^{126}Xe (N.A.=0.089%) can also undergo 2νECEC, but it is much slower due to smaller Q-value (896keV).

$^{124}_{53}$I 2^- 4.2d

0^+ $^{124}_{54}$Xe

Q_{ECEC}=2864keV

0^+

$^{124}_{52}$Te

ν K-shell X-ray

Xe   ···

ν K-shell X-ray

23

Limits on 2ν 2K-capture half-lives
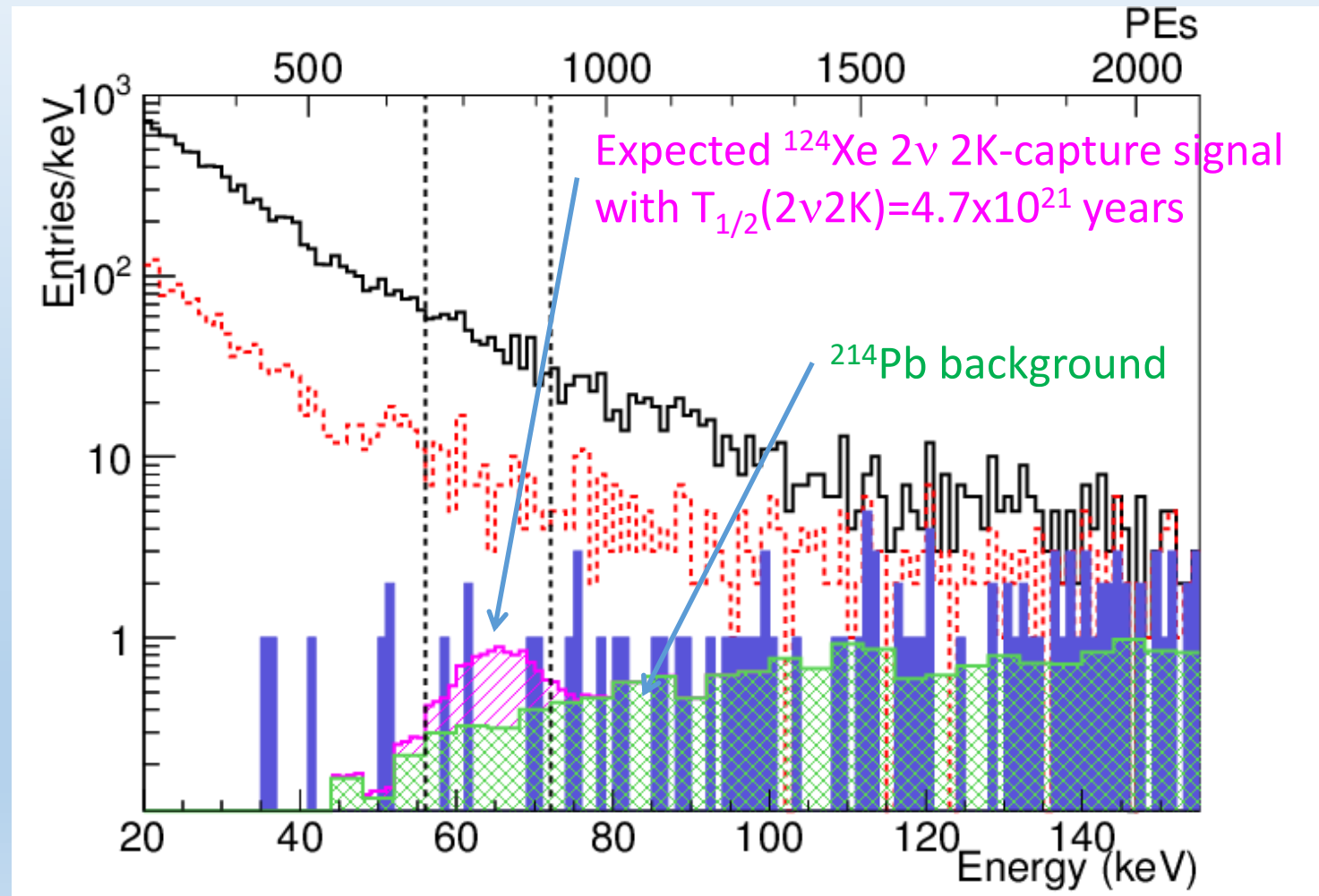
- We derived the 90% CL lower limit on ^{124}Xe 2νECEC half-life using the Bayesian approach.

- Since we do not see signal, we set limit on ^{126}Xe 2νECEC half-life as well.

$$T_{1/2}^{2\nu2K}(^{124}Xe) > 4.7 \times 10^{21} \text{ yrs}$$
$$T_{1/2}^{2\nu2K}(^{126}Xe) > 4.3 \times 10^{21} \text{ yrs}$$
(90%CL)

The world best limits to date !!
Published in Phys. Lett. B759 (2016) 64.

Comparison of background rate in fiducial volume including both nuclear recoil and e/γ events
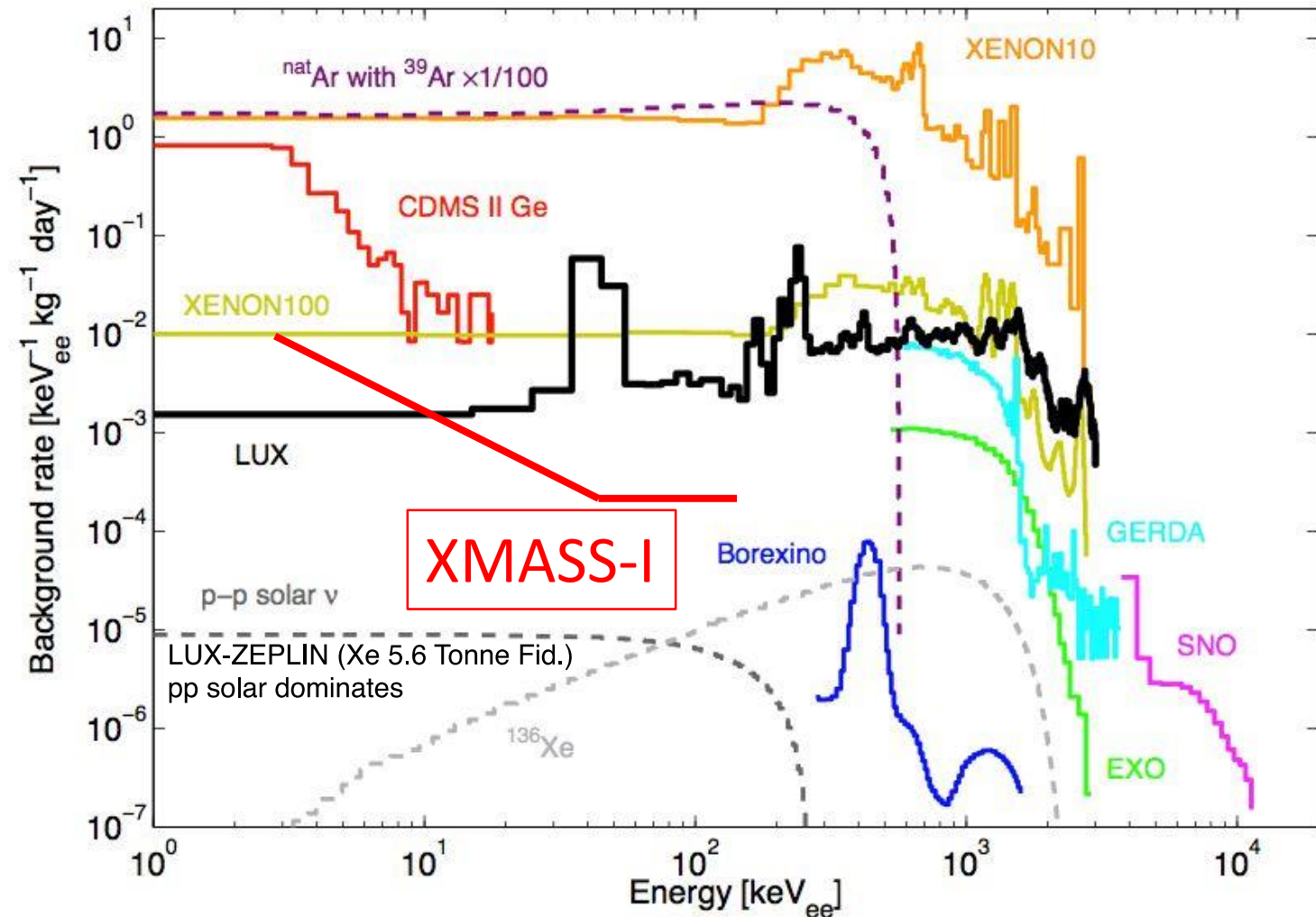
- XMASS achieved low background rate of $O(10^{-4})$ dru in a few 10s keV including e/γ events

- Low background rate for e/γ events is good for searching for dark matter other than WIMPs.

Original figure taken from
D. C. Mailing, Ph.D (2014) Fig 1.5

Inner calibration system

- Various RI sources can be inserted
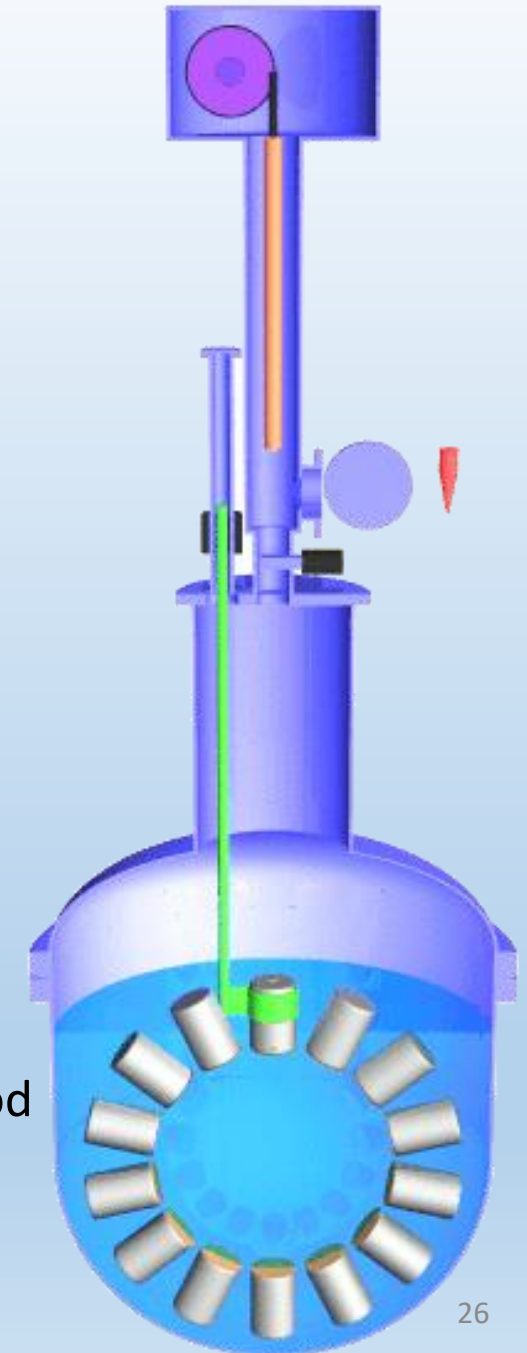- Used for light yield monitoring, optical parameter tuning, energy and timing calibrations etc.

| RI	Energy [keV]	Diameter [mm]	Geometry
^{55}Fe	5.9	10	2pi source
^{109}Cd	8, 22, 25, 88	5	2pi source
^{241}Am	17.8, 59.5	0.17	2pi/4pi source
^{57}Co	59.3 (W X-ray), 122	0.21	4pi source
^{137}Cs	662	5	cylindrical

^{57}Co source

19mm

0.21mm   4mm

Source rod (Ti)

Active region is concentrated on the 1.8 mm edge region

Measurement of LXe scintillation time profile for low energy gamma-ray induced events

- Using ^{55}Fe, ^{241}Am, and ^{57}Co sources ($E\gamma$=5.9-120keV)
- Waveforms are decomposed into "single PE" pulses
- MC simulation takes into account optical parameters (absorption, scattering, ...), electronics response
- Timing distributions of data and MC are compared to obtain intrinsic decay time parameters.
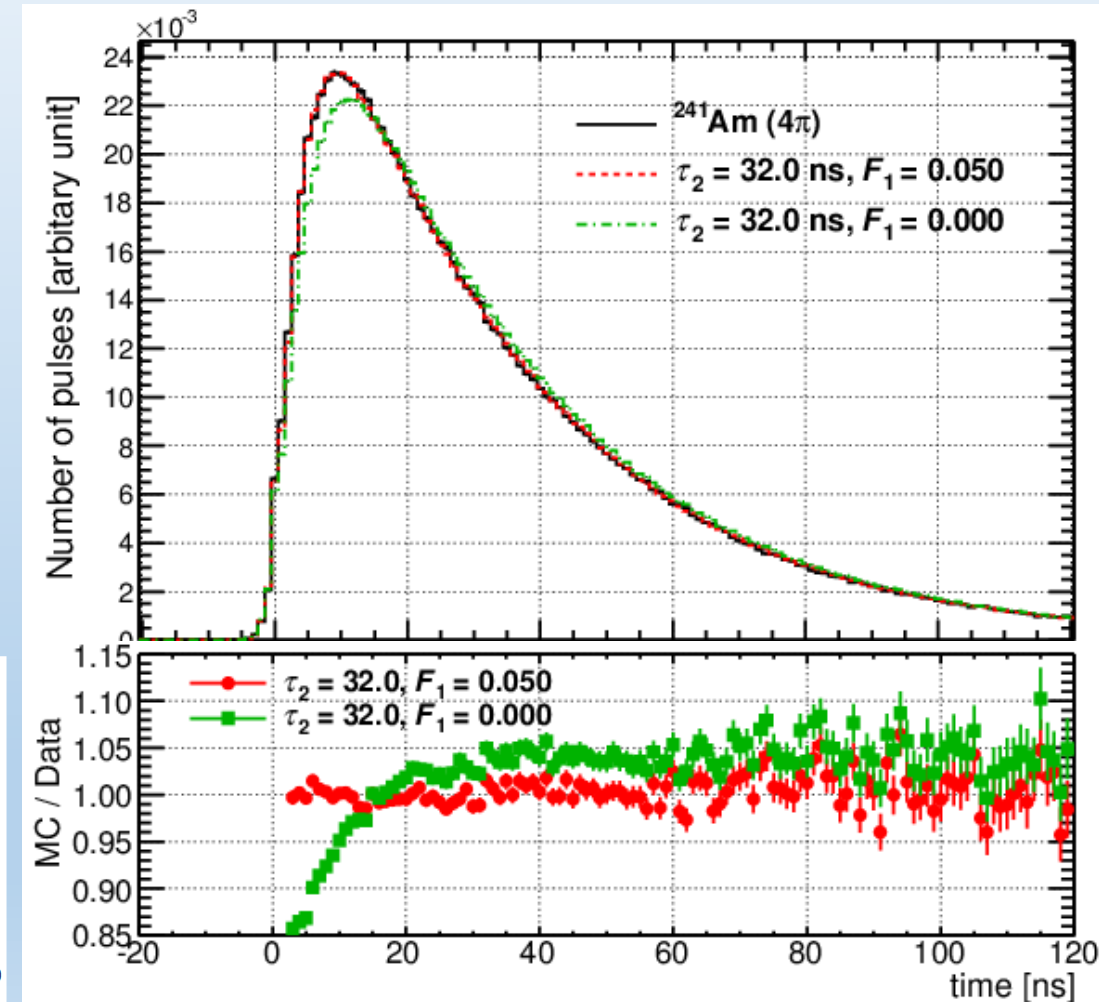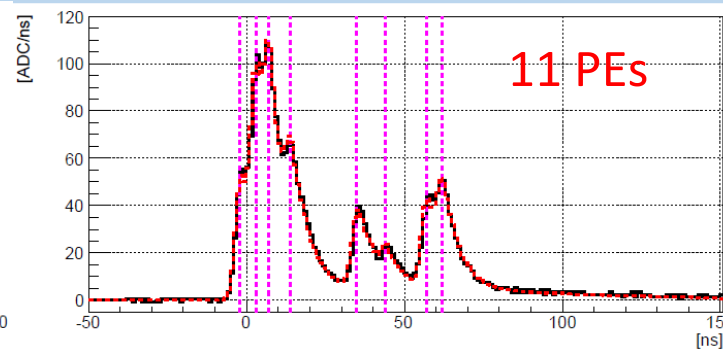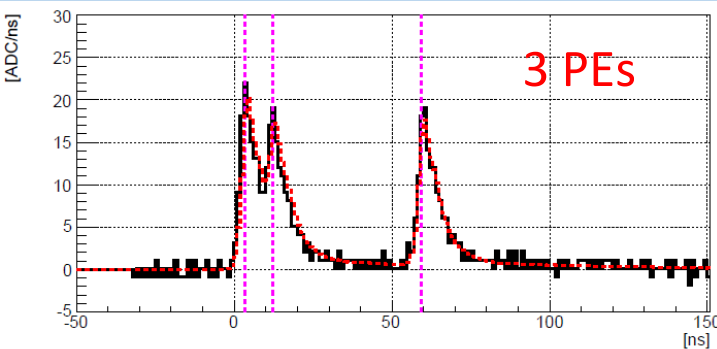
Measurement of LXe scintillation time profile for low energy gamma-ray induced events
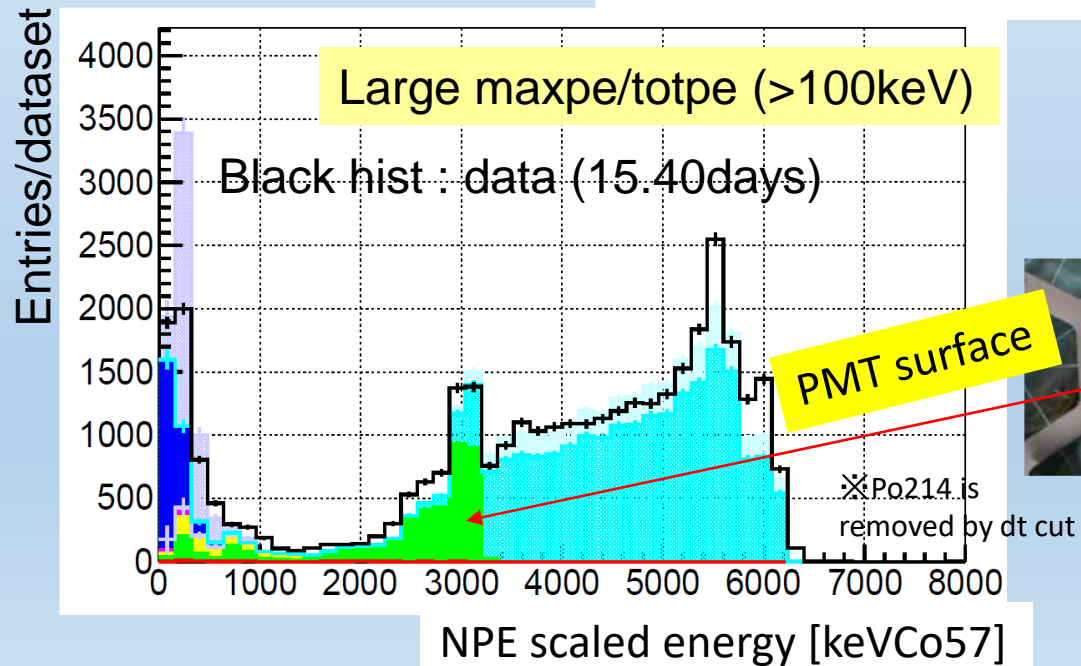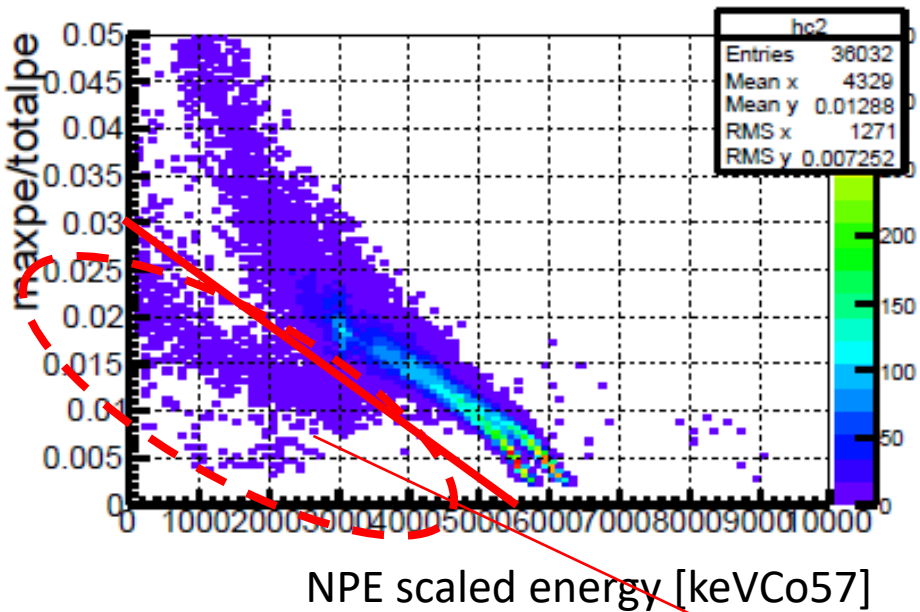
$$f(t) = \frac{F_1}{\tau_1} \exp\left(-\frac{t}{\tau_1}\right) + \left(\frac{1-F_1}{\tau_2}\right) \cdot \exp\left(-\frac{t}{\tau_2}\right)$$
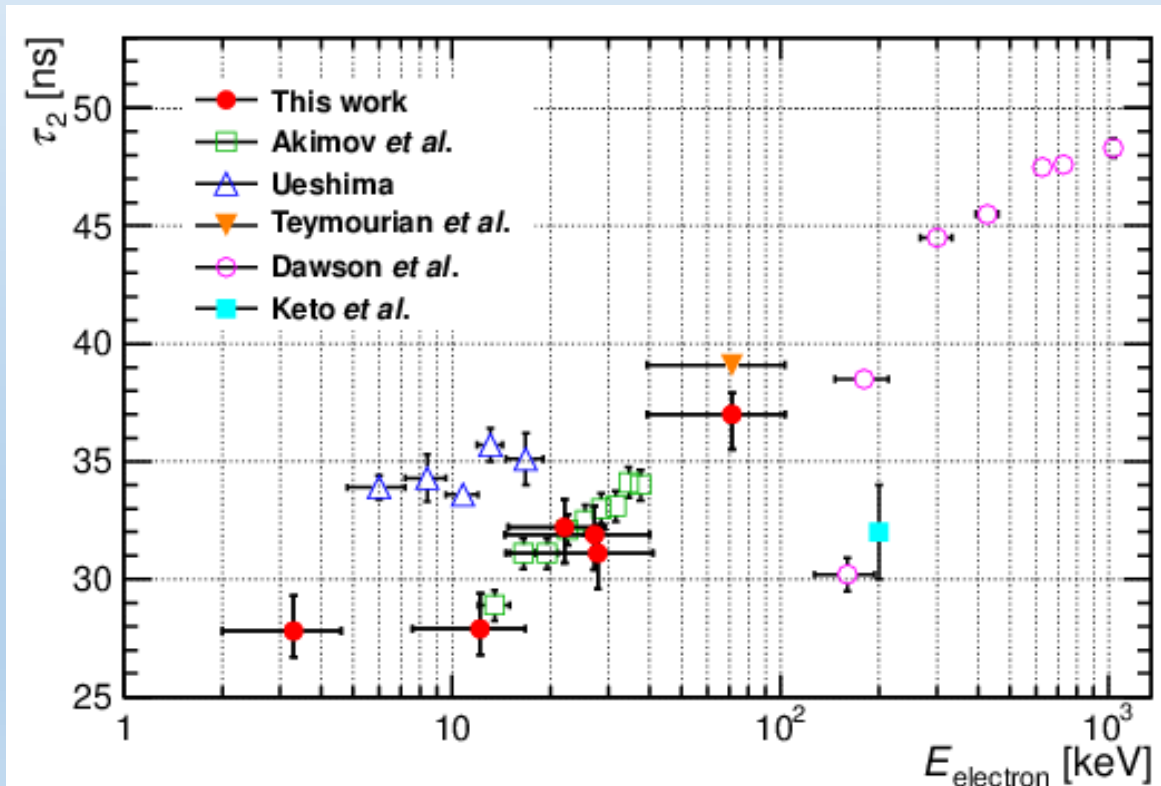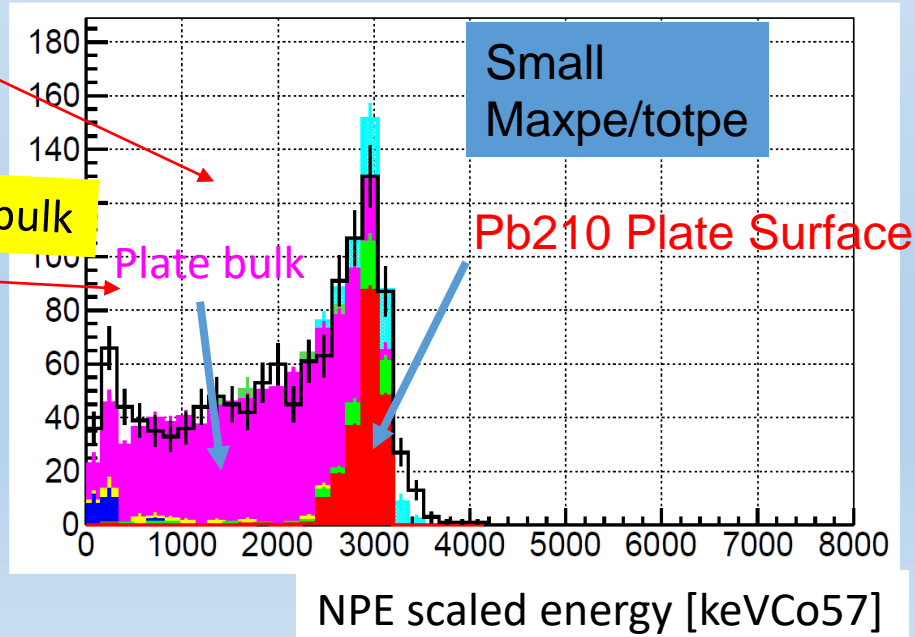

- Fast decay component is needed to reproduce our calibration data.
  - τ_1=2.2 ns (fixed)
  - F_1: 0.05~0.15 (increase at low energy)

- Energy dependence of decay time was studied as a function of mean kinetic energy of electrons induced by γ-ray
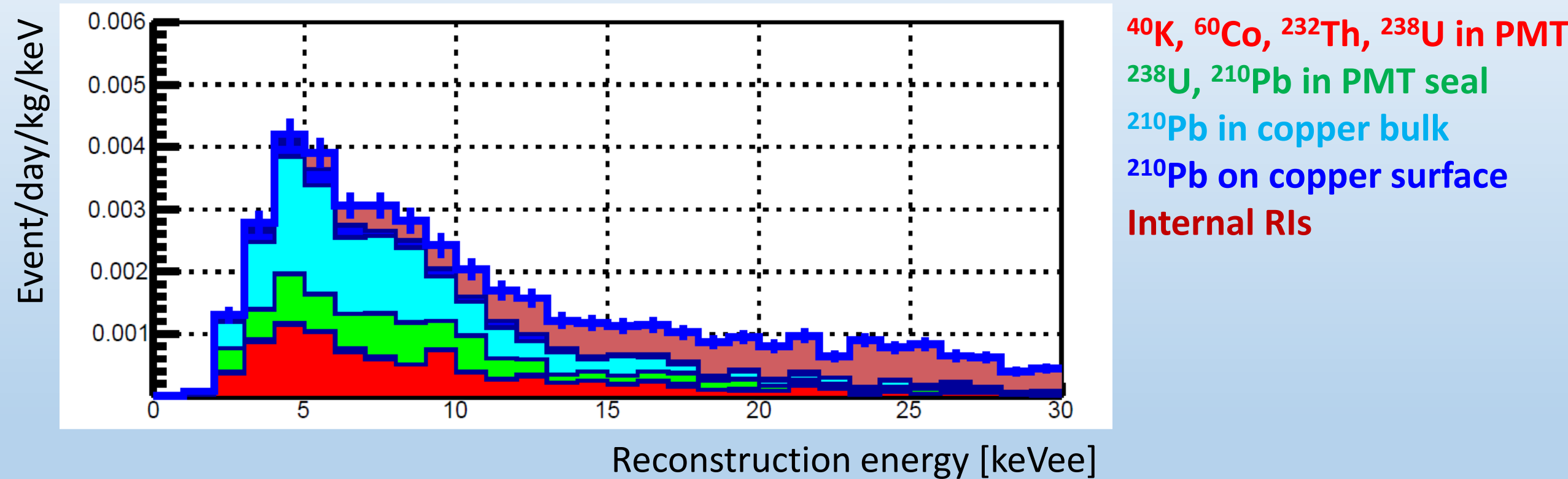
Nucl. Instrum. Meth. A834 (2016) 192

Alpha event spectrum :

RI	
Rn222Po218	(cyan)
Pb210Quartz surface	(green)
Pb210 Plate surface	(red)
U238Alseal	(blue)
Pb210Alseal	(blue)
Pb210 ring bulk	(yellow)
Pb210 Plate bulk	(magenta)

hc2
Entries 36032
Mean x 4329
Mean y 0.01288
RMS x 1271
RMS y 0.007252

maxpe/totalpe vs NPE scaled energy [keVCo57]

Large maxpe/totpe (>100keV)

Black hist : data (15.40days)

PMT surface

※Po214 is removed by dt cut

Entries/dataset vs NPE scaled energy [keVCo57]

Cu Plate surface/bulk

Small Maxpe/totpe

Plate bulk

Pb210 Plate Surface

NPE scaled energy [keVCo57]
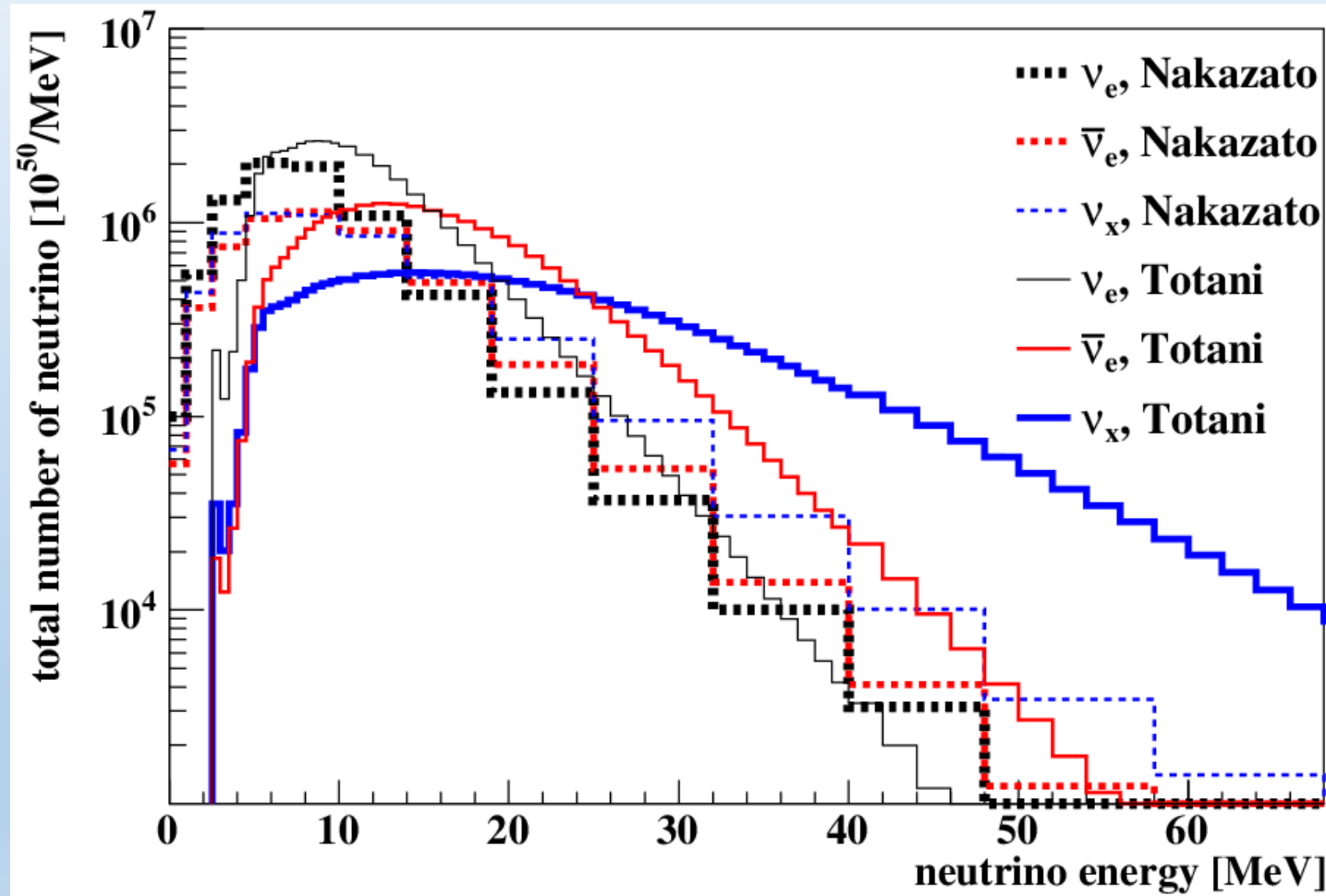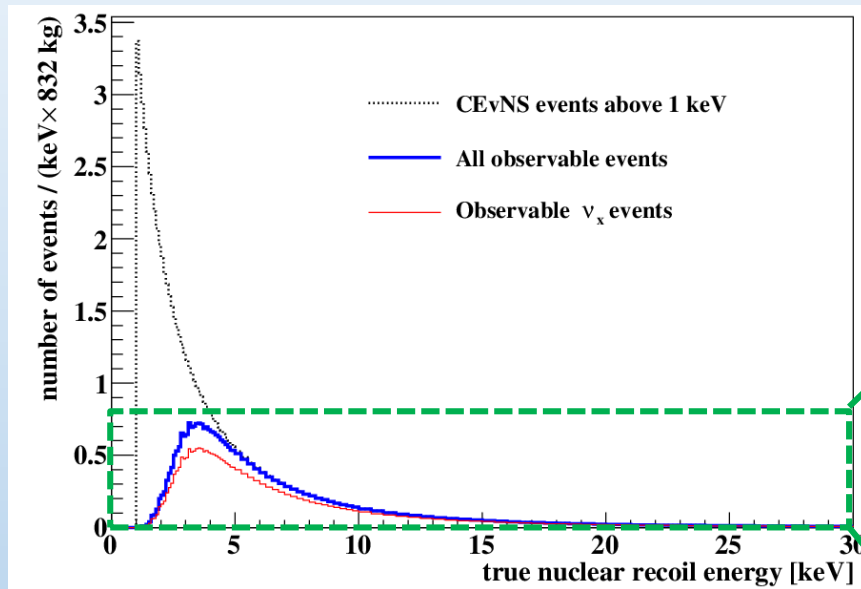
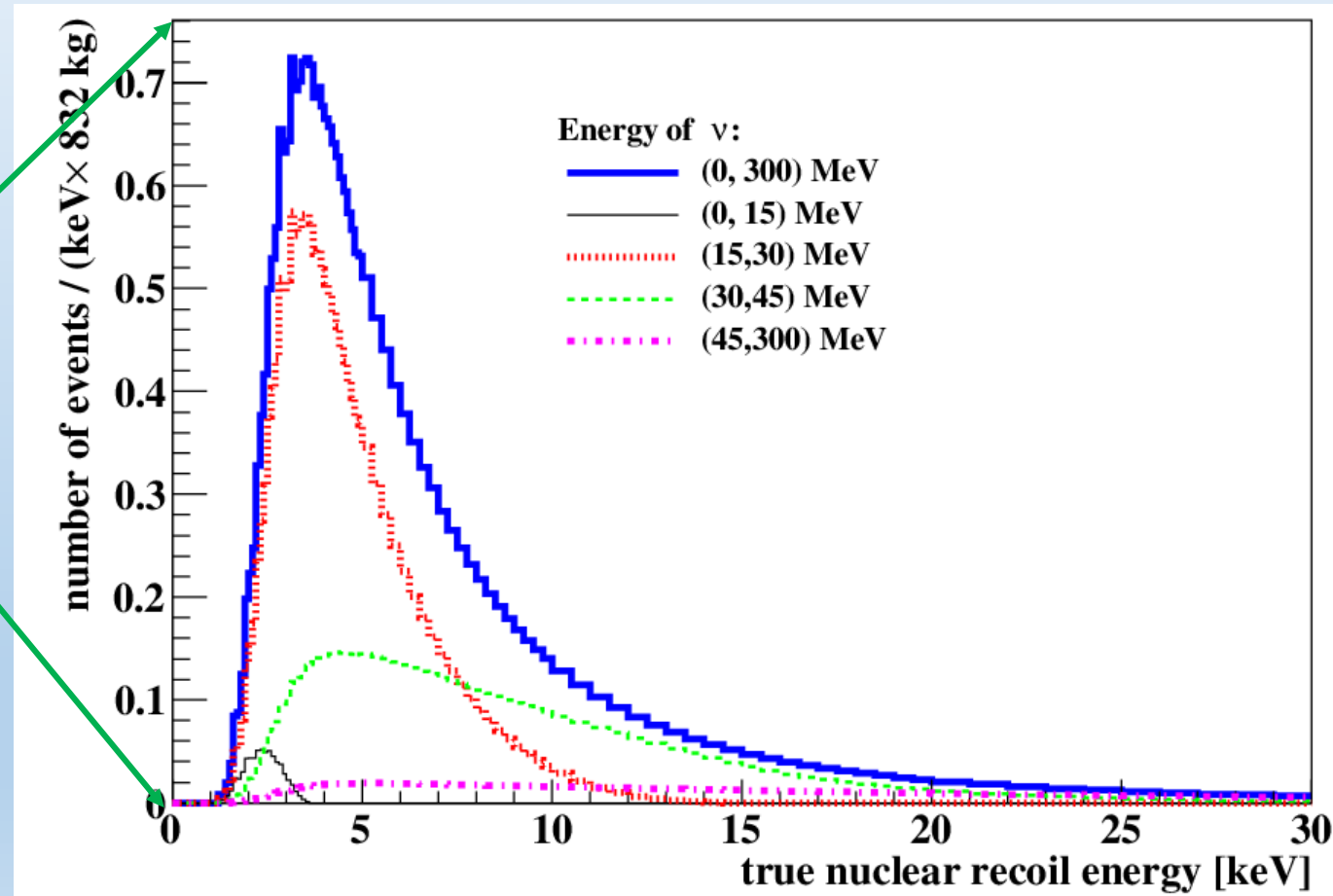# Composition of background after fiducialization

Supernova neutrino energy spectra

Nuclear recoil energy spectrum by supernova neutrinos

True nuclear recoil energy spectra for each neutrino energy

- XMASS can detect mainly ν_x
- Sensitive to neutrinos with $E\nu > 15 \text{MeV}$

Expected time profile of supernova neutrino events in XMASS

Livermore model
--- All events above 1keV
--- Observable events

Nakazato model
(20M$_{solar}$, Z=0.02, t$_{rev}$=200ms)
--- All events above 1keV
--- Observable events